Midas

MARGINAL LANDS, INDUSTRIAL CROPS
AND INNOVATIVE BIO-BASED VALUE CHAINS

Deliverable D1.1

Marginal land Classification and Information System (MIDAS-MLCIS 1) for low ILUC feedstock and current and future expectations on soil erosion, water stress and ecosystem services conditions

Funded by the European Union

This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement No. 101082070.

Document summary

Deliverable number	D1.1
Title	Marginal land Classification and Information System (MIDAS-MLCIS 1) for low ILUC feedstock and current and future expectations on soil erosion, water stress and ecosystem services conditions
Version	1
Work package n°	1
Lead Beneficiary	WR
Authors	Berien Elbersen, Michiel van Eupen, Gerard Hazeu, Wouter Meijninger & Stephan Mantel
Submission date	31 December 2023
Dissemination Level	Public
Project acronym and title	MIDAS
Grant Agreement n°	No. 101082070
Project coordinator	Dr. Efi Alexopoulou
Reviewer	Dr. Efi Alexopoulou
Review date	December 2023

Statement of Originality
This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

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Executive summary

This report presents the first version of a spatial marginal land classification and information systems. The focus in this deliverable is on marginal land mapped for 2020 and 2050 for the EU27+UK territory taking account of climate change effects. The marginal land mapping approach builds on the marginal land mapping in MAGIC but involves an update of all input data where more recent and better data exists. It also maps future marginal lands by 2050 taking account of climate change expectations modelled at high spatial resolution in CHELSA V2. This is the first Deliverable of work package 1 of Midas. This first deliverable consists of this report and an online map viewer embedded in a Storymap (https://arcg.is/1PPKjm) to be made accessible via the MIDAS website (https://www.midas-bioeconomy.eu/the-project/).

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1 Introduction

1.1 Aim and context

This deliverable presents the first version of a spatial marginal land classification and information systems. It is the first Deliverable of work package 1 of Midas that has as an overall objective **to improve understanding of the actual and future available marginal land in EU plus UK and Serbia and its potential for "low-ILUC" biomass production and for identification of co-benefits potential risks and upscaling of biomass production with a low potential for ILUC.**

This first deliverable consists of this report and an online map viewer embedded in a Storymap (https://arcg.is/1PPKjm) to be made accessible via the MIDAS website (https://www.midas-bioeconomy.eu/the-project/).

The focus in this deliverable is on marginal land mapped for 2020 and 2050 for the EU27+UK territory taking account of climate change effects. The marginal land mapping approach builds on the marginal land mapping in MAGIC but involves an update of all input data where more recent and better data exists. It also maps future marginal lands by 2050 taking account of climate change expectations modelled at high spatial resolution in CHELSA V2 (Climatologies at high resolution for the earth's land surface areas).

1.2 Method and approach

The method for mapping marginal land for 2023 (current) and future 2050 situation is similar to the one developed and used in MAGIC project (Elbersen et al., 2018). A summary of the MAGIC approach is presented in section 2.1 of this report. In this MIDAS work the MAGIC marginal land map is updated with newer and better data for both climate indicators and soil data. The steps followed to generate the updated marginal land map for the current and 2050 situation are as follows:

1) Review of data used for MAGIC marginal land map and identification of more up to date and better-quality data for all factors combined in the marginal land map
2) Review of available and most suitable climate (change) data to be used for the marginal land mapping 2023 and 2050 consulting climate change modelling experts at Wageningen Research
3) Collection and processing of new required data for marginal land mapping 2023 and 2050
4) Integration of data into updated marginal land maps 2023 and 2050
5) Evaluation of results including sensitivity analysis comparing uses of different climate change model outputs
6) Generation of maps, statistical summaries, and reports
7) Preparation of online map viewer and storymap.

1.3 Outline of report and online product: marginal land classification and information system (MLCIS)

This report consists of 4 chapters including this introductory chapter. In chapter 2 the way marginal lands are mapped for 2023 and 2050 is explained in detail. First it is discussed how marginal lands were mapped in MAGIC and how this was further updated in now in MIDAS for the current marginal

land status. An overview is provided per factor what input data is used, how this data was processed and what thresholds were exactly applied.
This is followed by the detailed description of the mapping of marginal lands in 2050. Emphasis is placed on a discussion of the climate change input data that are based on a careful selection of most suitable newest generation climate simulations using different models. For the use of the marginal land mapping, several climate simulation results needed to be further processed into indicators needed for the marginal land mapping. In chapter 3 the marginal land 2023 and 2050 results are presented and discussed. Chapter 4 presents a further characterization of the marginal land 2023 and 2050 and discusses next steps in Midas in relation to low ILUC risk land assessment.

2 Marginal land mapping

2.1 Marginal land mapping in MAGIC

In MAGIC project the marginal land mapping took the biophysical constraints in the framework proposed for identifying 'areas of natural constraints' in the EU by the European Commission Joint Research Centre (JRC) (Van Oorschoven, et al., 2014 and Terres et al, 2014) as a starting point. This was also combined with rules used in evaluation systems for classifying lands suitable for cropping and pasturing/grazing and those that are less or not suitable (e.g. USDA-Land Capability Classification System (LCC) , Muencheberg by Mueller et al., 2010; Soil Quality Rating by Shepherd, 2000; Murray et al. , 1983, and Louwagie et al., 2009).

In MAGIC biophysical factors have been identified for the classification of severe limitations for crop production; **18 single factors, grouped into 6 clustered factors**. These 6 clusters were grouped determining marginal lands (see Table 1). These clustered biophysical factors are considered major environmental characteristics that, when critical threshold values are exceeded, they are (severely) limiting agricultural production. Critical limits were defined for severe and sub-severe classes for each individual factor making up the 6 clustered factors (See Table 1). The objective of MAGIC was to design and apply a method that is transparent (the resulting marginal land classes results can be interpreted back to the determining single factors), simple and repeatable. If factors meet the threshold value they are categorized as '**severe**' which makes them qualify as marginal. Factors can also score within the 20% margin of the threshold value of severity and then they are categorized as '**sub-severe'**. These sub-severe classes can be included in the marginal land class in case they fall in a **pairwise combinations** with another single factors scoring sub-severe. Their combination may jointly aggravate (negative combination) or counterbalance (positive combination) the limiting conditions (based on Terres et al., 2014). The simplified approach of mapping marginal land in MAGIC was considered appropriate since major limitations for agriculture are identified, rather than optimal conditions for plant growth and land management.

The first clustered factor is **adverse climate** and is composed of two parameters as proposed in the JRC approach to mapping areas of natural constraints (van Oorschoven et al., 2014): low temperatures and drought. Very low temperatures exclude or limit growth of many agricultural crops. As an indicator for **low temperatures** the Length of Growing Period was used of: number of days (threshold at 180 days) with daily average temperature > 5°C (LGPt5) or Thermal-time sum (growing degree-days; threshold at 1500 degree days) for Growing Period defined by accumulated daily average temperature > 5°C. This is calculated as follows:

$$\mathrm{GDD} = \left[\frac{(T_{\mathrm{MAX}} + T_{\mathrm{MIN}})}{2}\right] - T_{\mathrm{BASE}}$$

Where:

T_{max} *and* T_{min} *= daily maximum and minimum temperature*

T_{base} *= in this case it is* 5°C.

For **dryness** the ratio of precipitation over potential evapotranspiration is indicative of soil moisture conditions for agricultural crops. In case of low rainfall and high evaporative demand then the soil moisture supply will be low and the growth potential for crops is low. The indicator for dryness is assessed by taking the ratio of the annual precipitation (P) to the annual potential evapotranspiration (PET). The threshold is set at 0.5 (P/PET ≤ 0.5). It is clear that the change of the adverse climate factors will be most influenced by climate change and are therefore most significantly influencing on the future location of marginal lands by 2050 as will be further discussed in Section 2.3.

The second clustered factor is **excessive wetness**. Excess of soil moisture (water content above field capacity) over prolonged time in the field is limiting for crops and for management. Access of the field with machines and the workability of the soil is hampered and lack of oxygen for root growth limits crop growth. This is evaluated by soil moisture content exceeding field capacity for at least 210 days (7 months). The second parameter within this clustered factor is soil drainage status which is a morphometric parameter that reflects the combined effects of climate, landscape and soil. It is described in the field and is indicative for the wetness of a soil over longer periods of time (and that is reflected in the soil status, judged by a.o. soil colour and mottling). The poorly drained soils from WRB (at Soil Reference Group level and at the level of principle qualifiers) were selected from the European Soils Database (Table 1). Also this factor will be influenced by climate change and will therefore be of importance to identify the future location of marginal lands.

The third cluster is called **adverse chemical conditions**. It combines the excess of salts and toxic elements in the soil that hamper crop growth or may pose a health risk. The excess of salts affects crop growth in various ways: by toxicity effects, by reducing the water availability to plants through increased osmotic pressure and by causing nutritional disorders. Excess of salts occurs through salinity (access of free salts) and sodicity (saturation of the soil exchange complex with sodium), (Mantel and Kauffman, 1995). **Salinity** is identified through units on the soil map of Europe (European Soils Database) which were mapped in the ESDAC project (Toth et al., 2018). Solonchaks soils and soils with a salic qualifier that cover more than 50% of the mapping unit area were ranked as highly saline (ECse > 15 dS/m). **Sodicity** was mapped from the same source (ESDAC). It is derived from the mapping units that have more than 50% area of sodic soils (Solonetz) and soils with a sodic qualifier. Sodic soils are soils with saturation of the exchange complex with sodium (ESP) of more than 15%.
There are several **naturally occuring toxicities** in soils that have a negative effect on crop growth. In acid subsoils this may be caused by high aluminium contents. Since aluminium toxicity is not well represented in the soil databases available it was not possible to include this factor in the MAGIC marginal land map. This did not apply to the acid sulphate soils as these were identified through the Thionic qualifier of soils in the European Soils Database. The reason these acid sulphate soils are limiting agricultural use is because when they are drained, which happens when they are used for arable agriculture, they become extremely acidic, as sulfides react with oxygen to form sulfuric acid. Extremely high acidity, high sulfur availability and aluminium toxicity that result in drained acid sulphate soils are posing great limitations to land management for farming.

The fourth cluster was formed by **low soil fertility**. This factor is formed by various parameters. It refers to the availability of nutrients over time to crops. Soil nutrient availability is often highly variable in both space and time and depends on many variables. Here two parameters that influence soil fertility were ranked: soil reaction (pH) and organic carbon content. **Soil reaction** is an indicator for the availability of nutrients (poor in alkaline and in acid soils). Soils with pH (0-30 cm) below 4.5 or above 8 are considered (severely) limited. **Organic carbon** contributes to the nutrient buffering capacity of the soil and organic matter is a direct source of nutrients. Low carbon containing soils are indicative for low soil fertility and low biomass turnover.

Table 1 Overview of biophysical constraints used to map marginal lands in MAGIC, thresholds and data used (source: Elbersen et al., 2018)

Cluster	Sub- factor	Description	Selection based on (JRC, Meuncheberg, other...)	Threshold for marginal lands	Data source used for mapping
1. Adverse climate	a. Low temperature	Length of Growing Period: number of days with daily average temperature > 5°C (LGPt5) or Thermal-time sum (degree-days) for Growing Period defined by accumulated daily average temperature > 5°C.	JRC (Van Oorschoven et al, 2014)	LGPt ≤ 180 days Or Degree days <= 1500 days (<= 1575 = sub-severe)	CRU CY v. 3.24. Climatic Research Unit - CRU (1901-2015). Harris et al. (2014) doi:10.1002/joc.3711
	b. Dryness	Ratio of the annual precipitation (P) to the annual potential evapotranspiration (PET). Thresholdlimit: (P/PET ≤ 0.5)	JRC (Van Oorschoven et al, 2014)	P/PET ≤ 0.5 (< 0.6 = sub-severe)	CRU CY v. 3.24. Climatic Research Unit - CRU (1901-2015). Harris et al. (2014) doi:10.1002/joc.3711
2. Excessive wetness	a. Excess soil moisture	Water content in the soil exceeds field capacity for at least 210 days (7 months)	JRC (Van Oorschoven et al, 2014) with slight adaptation for threshold to follow mapped classes.	210 days severe (190 days = sub-severe)	CRU CY v. 3.24. Climatic Research Unit - CRU (1901-2015). Harris et al. (2014) doi:10.1002/joc.3711
	b. Limited soil drainage	Soils with high water tables throughout the year that have a lack of oxygen in the rooting zone, effectively limiting growth of crops	JRC (Van Oorschoven et al, 2014) but with adapted thresholds/selections from the Reference Soil Groups (RSGs) of the World Reference Base for Soil Resources	Gleysols, Histosols, Stagnosols, Planosol, Soils with primary qualifiers Histic, Gleyic and Stagnic and marshlands with >60% clay (>50% = sub-severe)	ESDB v2.0: The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004
3. Adverse chemical conditions	a. Salinity (Ec)	Soils with high salinity content	Toth et al. (2008) and Van Oorschoven et al (2014)	Solonchaks and soils with a salic qualifier. For these salt level > 15 dS/m and more than 50% of the mapping unit area (sub-severe <50% of the mapping unit)	Toth et al., (eds) (2008), Threats to soil quality in Europe. EUR 23438 EN - 2008 and https://esdac.jrc.ec.europa.eu/content/saline-and-sodic-soils-european-union
	b. Sodicity (Na – ESP)	Soils with high sodicity content	Toth et al. (2008) and Van Oorschoven et al, (2014)	Solonetz, 'natric' soils, or 'Sodic' soils. Saturation with exchangeable sodium of more than 15% (ESP), and more than 50% of the mapping unit area (sub-severe <50% of the mapping unit)	https://esdac.jrc.ec.europa.eu/content/saline-and-sodic-soils-european-union and ESDB v2.0: The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004
	c. Natural toxicity (e.g. Al, S)	Soils with high content of sulfur that have acidification potential upon drainage	JRC (Van Oorschoven et al, 2014) but with adapted thresholds/selections from the Reference Soil Groups (RSGs) of the World	Soils with Thionic qualifier	ESDB v2.0: The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004
	d. Toxicity by pollutants	Soils that have been polluted by man mostly through waste disposal or industrial processes	Data not included yet (Toth et al, 2016)	NOT INCLUDED YET	Data currently not available to the project: Tóth, G., et al. (2016). "Heavy metals in agricultural soils of the European Union with implications for food safety." Environment International 88(Supplement C): 299-309. doi.org/10.1016/j.envint.2015.12.017

Cluster	Sub- factor	Description	Selection based on (JRC, Meuncheberg, other...)	Threshold for marginal lands	Data source used for mapping
4. Low soil fertility	a. Soil reaction (pH)	Highly acidic and alkaline soils (0-30 cm)	JRC (Van Oorschoven et al, 2014) (with adapted threshold values)	Soils with pH below 4.5 or pH above 8 (at depth 0-30 cm) (sub-severe < 5 pH)	Hengl, T., Mendes de Jesus, J., Heuvelink, G. B.M., Ruiperez Gonzalez, M., Kilibarda, M. et al. (2017) SoilGrids250m: global gridded soil information based on Machine Learning. PLoS ONE 12(2): e0169748. doi:10.1371/journal.pone.0169748
	b. Soil organic carbon (%)	Low organic carbon containing soils as an indicator for soils with low fertility and low biomass turnover (0-30 cm)	Based on Mantel et al (2010)	SOC % average of depth range 0-30 cm at <0.5% (<0.75% = sub-severe)	Hengl, T., Mendes de Jesus, J., Heuvelink, G. B.M., Ruiperez Gonzalez, M., Kilibarda, M. et al. (2017) SoilGrids250m: global gridded soil information based on Machine Learning. PLoS ONE 12(2): e0169748. doi:10.1371/journal.pone.0169748
5. Limitations in rooting	a. Unfavourable soil texture	Texture class in half or more (cumulatively) of the 100 cm soil surface is sand, loamy sand defined as: silt% + (2 x clay%) ≤ 30%	JRC (Van Oorschoven et al, 2014) but with adapted thresholds/selections	Sand, loamy sand defined as: silt% + (2 x clay%) ≤ 30% (=> Max 70% sand) (max 60% sand = sub-severe)	AGLIM1 : Code of the most important limitation to agricultural use of the STU https://esdac.jrc.ec.europa.eu/resource-type/european-soil-database-maps ESDB v2.0: The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004
	b. Coarse fragments & surface stones	> 35 cm (0-30 cm)	JRC (Van Oorschoven et al, 2014) but with adapted thresholds/selections	Course material At depth: 0-35 cm covering a surface of >35% and/or > 15% rock coverage (> 25% and/or > 10% respectively for sub-severe)	AGLIM1 : Code of the most important limitation to agricultural use of the STU https://esdac.jrc.ec.europa.eu/resource-type/european-soil-database-maps ESDB v2.0: The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004
	c. Organic soils	Organic matter ≥ 20%)	JRC (Van Oorschoven et al, 2014) but with adapted thresholds/selections	>= 20% organic matter = Histosols	ESDB v2.0: The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004
	d. Shallow rooting depth	Depth (cm) from soil surface to coherent hard rock or hard pan	JRC (Van Oorschoven et al, 2014) but with adapted thresholds/selections	< 30 cm rooting depth possible. Selected soils for mapping: Leptosols, Albeluvisols, Lithic, Petrocalcic, Fragipans, Duripans, Petroferric	AGLIM1 : Code of the most important limitation to agricultural use of the STU https://esdac.jrc.ec.europa.eu/resource-type/european-soil-database-maps ESDB v2.0: The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004
6. Adverse terrain conditions	a. Steep slope	Change of elevation with respect to planimetric distance (%).	JRC (Van Oorschoven et al, 2014) but with adapted thresholds/selections	>80% of area has a slope of > 15% slope > 60% of the area has a slope of >15% slope = sub-severe)	European Digital Elevation Model (EU-DEM), version 1.1
	b. Flood risk	Risk of flooding in relation to risk of damage to the field and to crops during the growing season	Meuller et al. (2011)	> 2 m flood in 2yrs return time (>1-2 m flood in 2 yr return time (=sub-severe)	JRC_Lisflood_2025 2 Years Return rate. Dankers, R. and L. C. D. Feyen (2009). "Flood hazard in Europe in an ensemble of regional climate scenarios." Journal of Geophysical Research: Atmospheres 114(D16). DOI 10.1029/2008JD011523

The threshold was set at 0.5% carbon (lower is severely limited). Sandy soils (most of which are poorly fertile and have a low nutrient content) are not considered here as they are addressed in the last cluster of 'limitations in rooting' (see next).

The fifth cluster is **limitations in rooting**. Root growth is directly related to possibility for uptake of nutrients and water and provides food for the crop. Root growth constraining factors selected were: unfavourable soil texture, coarse fragments, organic soils, surface stones and rocks, and shallow rooting depth. **Unfavourable texture** concerns the sandy soils and the heavy clays. Very sandy soils have a low water holding capacity and are often low in nutrient content and nutrient buffering capacity. Normal fertilization practices have limited efficiency on very sandy soils (Van Oorschoven, J., et al., 2014). Heavy clays are limiting for crop cultivation as they have limitations in access for machinery during wet parts of the season, difficult workability and may have shrinking and swelling characteristics during dry and wet conditions that may damage plant roots. Water movement may be slow in heavy clays (due to low porosity) and water may accumulate on the surface in high rainfall events. The presence of **coarse fragments** limits crop cultivation because the negative effect on workability. The volume occupied by coarse fragments limits rootable space and the volume of storage for water and nutrients in the soil. **Surface stones and rocks** are another limitation for soil workability and access of machinery. Furthermore, surface stones and rocks hamper seed germination. The threshold for severe was set for a surface coverage (at depth: 0-35 cm) by coarse fragments at >35% and/or > 15% with rock coverage. For sub-severe level the thresholds of surface coverage were (> 25% and/or > 10% respectively.

Organic soils are soils with organic matter content ≥20% in a layer of 40 cm or more, either extending down from the surface or taken cumulatively within the upper 100 cm of the soil (histic horizon, IUSS Working Group WRB, 2006). Foothold for roots is limited in organic soils, especially for perennial crops. Peatlands are typical examples of where organic soils occur and they are both ecologically valuable and fragile. Cultivation of organic soils requires drainage and this causes oxidation of the peat and methane release. Peat soils are therefore best left uncultivated.

Shallow rooting depth is defined as the depth in cms from soil surface to coherent hard rock or hard pan. The rootable soil volume is a critical characteristic of land in relation to suitability for farming. It determines the foothold for roots, but most of all the total store of nutrients and water that will be potentially available to the plant during the growing season. Rootable soil volume may be limited by chemical or physical barriers. In assessment of marginal lands a shallow depth from the soil surface to an impeding layer (hardpan) or to bedrock (30 cm or less in Leptosols) is considered.

For the last cluster **adverse terrain conditions** MAGIC considered two factors namely slope and flooding risk. **Steeply sloping** lands are a limitation for land access with machines, but also for water infiltration capacity. On sloping land less water infiltrates into the soil and surface runoff leads to erosion. The slope is described as the change of elevation with respect to planimetric distance (%). The threshold for severe was set at slopes of ≥ 15% covering >80% of the area. Thresholds for sub-severe were set at 15% slopes covering between 80% and 60% of the area. **Flooding** is a risk for crops on the field as they may be damaged directly through the resistance of the water flow and the resulting (prolonged) water ponding may damage crops. Thresholds were set for severe class at > 2 m flood in 2yrs return time and for sub-severe they are at >1-2 m flood in 2 yr return time.

Pairwise combinations of sub-severe single factors in MAGIC

The concept of the pairwise combinations of sub-severe biophyscial factors is that they have a different impact on agricultural productivity than either of these two specified criteria acting independently at sub-severe threshold levels. The agronomic rationale for the pairwise combinations is presented in Terres et al. (2014). A summary of the pairwise combinations involved and how they lead to an aggravation or neutralization of the limitation is presented in **Error! Not a valid bookmark self-reference.**.

Following the method as described by Terres et al. (2014), pairwise combinations, 24 in total, were made in MAGIC (26 in MIDAS) to assess possible negative (-) and positive (+) synergies and interactions of biophysical factors (see Table 2, third column). The land units were identified with biophysical factors within the 20% margin of the threshold value of severity. This allows to map areas with one or more factors close (within 20%) of the threshold. i.e. the sub-severe level. When two factors are within sub-severe level the land units can be classified from sub-severe to severe provided the combinations in Table 1Table 2 are applicable. So, if in the third column (Table 2) a '-'is indicated it means that the two combinations in sub-severe level become severe, so marginal. If the score is '+' then the combination will remain sub-severe, even if one of the 2 factors scores severe. To illustrate the logic we can take the factor 'low temperature' scoring sub-severe (= between 1500 and 1575 degrees Tsum) in the pairwise combination with heavy clay also being sub-severe (60%>clay<50%). This pairwise combination then becomes severe, so marginal.

Table 2 Overview of pair wise combinations of biophysical factors used (elaborated from Terres et al., 2014). In the last 2 columns the left column specifies the severe limit (automatically marginal) and the right column the sub-severe which is marginal in the pairwise combination (indicated in the second column)

Cluster	Pairwise combination	+/-	Thresholds	
			Marginal limit	**Within 0-20% of limit**
1A - Low temperature			1500 degrees Tsum	1575 degrees Tsum
	Excess soil moisture	-	210 Days/Year	190 Days/Year
	Heavy clay	-	> 60% clay	> 50% clay
	Organic soil	-	Peat Soils	NA
1B - Dryness			P/PET ≤ 0.5	> 0.5 P/PET < 0.6
	Stoniness	-	Coarse fragments covering > 35% surface and/or stones>15%	Coarse fragments covering > 25% surface and/or stones>10%
	Sand, loamy sand	-	> 70% sand	> 60% sand
	Heavy clay	-	> 60% clay	> 50% clay
	Rooting depth	-	Lithic-/Leptosols (WRB)	Lithic-/Leptosols (WRB)
	Salinity	-	> 50% of the area	< 50% of the area
	Slope	-	>80% of area has a slope of > 15% slope	> 60% of the area has a slope of >15% slope
2A Excess soil moisture	Organic soils	-	Peat Soils	NA
	Rooting depth	-	Lithic-/Leptosols (WRB)	Lithic-/Leptosols (WRB)
	Slope	+	>80% of area has a slope of > 15% slope	> 60% of the area has a slope of >15% slope
2B Poor drainage	-		Lithic-/Leptosols (WRB)	Lithic-/Leptosols (WRB)
3. Adverse chemical conditions	-		-	-
4. Low soil fertility	Low SOC - In MIDAS adapted!		In MAGIC <0.75% SOC In MIDAS: <1 % SOC	In MAGIC <1% SOC In MIDAS: <1.25%
	Slope	-	>80% of area has a slope of > 15% slope	> 60% of the area has a slope of >15% slope
	Dryness	-	P/PET ≤ 0.5	> 0.5 P/PET < 0.6
5. Rooting conditions				
5A –Sand, loamy sand	Organic soil	+	Peat Soils	NA
	Salinity/sodicity	-	Soil affected soil types > 50% of the area coverage	Soils affected soil types < 50% of the area coverage
	Rooting depth	-	Lithic-/Leptosols (WRB)	Lithic-/Leptosols (WRB)
5A – Heavy clay	Rooting depth	-	Lithic-/Leptosols (WRB)	Lithic-/Leptosols (WRB)

Cluster	Pairwise combination	+/-	Thresholds	
	Salinity/sodicity	-	> 50% of the area	< 50% of the area
	pH	-	<4.5 or > 8	< 5
5B – Stoniness	Sand, loamy sand	-	> 70% sand	> 60% sand
	Organic soil	+	Peat Soils	NA
	Rooting depth	-	Lithic-/Leptosols (WRB)	Lithic-/Leptosols (WRB)
	Slope	-	>80% of area has a slope of > 15% slope	> 60% of the area has a slope of >15% slope
5C – Rooting depth	Salinity/sodicity	-	> 50% of the area	< 50% of the area
	Slope	-	>80% of area has a slope of > 15% slope	> 60% of the area has a slope of >15% slope
6. Adverse terrain conditions	-		-	

'-' =Negative pairwise combination
'+'=Positive relation leading to neutralization, so the combination is not classified as severe _=marginal), even if one of the factors is severe already.

The pairwise combinations with low Soil Organic Carbon (in 4 in Table 2) were not yet implemented in the MAGIC project, but are now added in the MIDAS project. For further details, see next section 2.2.

Correction for human management

The last step taken in MAGIC for the mapping of marginal lands was the application of a correction of the marginal land map based on natural biophysical limitations for human management. There are lands that have natural constraints, but these have been **neutralised by human interference, making them well suited for normal and even high productive agriculture.** This implies that although originally natural constraints were present, they are no longer limiting. These improved naturally constrained areas should be classified separately from the marginal land areas mapped. On the other hand, for the remaining biophysically constrained marginal lands, land management status also needs to be established. These can be uses of the unimproved marginal lands, e.g. for grazing or other forms of very extensive agriculture, or no uses, e.g. abandoned.

In Table 3 an overview is made of the main improvement measures and how their effect in terms of neutralizing the natural constraint situation can be spatially detected with existing data sources.

Table 3 Natural constraints and land management to convert marginal lands into productive lands and suggestions to best map the land management situation (copied from Elbersen et al., 2018)

Natural constraint	Land management improvement measure	Data sets used to detect & validate (directly/indirectly) the land management improvement measures
Adverse climate - dryness	Irrigation	1) Irrigated areas by crop. European Irrigation map aggregated to a grid of 100 m x 100m. (JRC, Wriedt, et al. 2009). 2) CLC irrigated areas (2012)
Excessive wetness - Limited soil drainage	Drainage	1) Active/managed cropland & grassland (Estel et al. (2015) based on NDVI index from MODIS) 2) CLC land cover map 2012

Natural constraint	Land management improvement measure	Data sets used to detect & validate (directly/indirectly) the land management improvement measures
Limiting soil fertility (Low SOC) and/or limitations in rooting	Soil fertility management & mulching	3) Combine CLC agricultural classes with Estel et al. classes identified as active management (≥ 8 times in 12 NDVI disturbances) and generate separate CLC management combinations: active cropland/active crops & grasslands/ active grassland/low productive cropland/low productive grasslands classes. 4) Land use intensity maps gridded in PEGASUS based on Perez-Soba et al., (2015), high, medium and low intensity farmland
Adverse terrain (slope)	Terraces & other slope management measures (mulching?)	1) Identify areas with slopes > 15˚ - to 25˚ 2) CLC land cover map 2012 3) Combine CLC agricultural classes with Estel et al. classes identified as active management (≥ 8 times in 12 NDVI disturbances) and generate separate CLC management combinations: active cropland/active crops & grasslands/ active grassland/low productive cropland/low productive grasslands classes.
All constraints	Establishment of green houses or other (intensive) agricultural buildings (e.g. mega-stables)	Overlay all areas with natural constraints with: • The Global Human Settlement Layer (2014) (Pasaresi et al., 2016) (30 m resolution)

2.2 Updates made in current Marginal land status mapping in MIDAS

In Midas the MAGIC marginal land mapping approach for identifying current marginal lands is updated with more recent and improved data. An overview of the updates made in MIDAS is presented systematically in Table 4. The most important changes were made by exchanging all climate data derived from CRU CY v. 3.24. in MAGIC by newer data from CHELSA V2 (Karger et al., 2017). CHELSA provides climate data at high spatial resolution for the earth's land surface areas.
The CHELSA data that were downloaded referred to:

- Daily mean/max./min. air temperature.
- Precipitation; amount per month
- GGD 5°C: heat sum of all days above the 5°C temp. accumulated over 1 year

In a pre-processing procedure (see for further details Annex I) the following parameters were derived:

- Sub-indicator (a) Low temperature which is expressed as thermal-time sum (degree-days) for growing period defined by accumulated over 1 year heat sum of all days above the 5°C temperature
- Aridity Index (AI) or degree of dryness, defined as annual precipitation divided by the annual reference evapotranspiration (PET).
- Monthly fraction of Soil Water Content (SWC) which is further to total number of days with saturated soil

For further details on the pre-processing steps see also Annex I explaining in detail the input data used and the pre-processing steps taken to prepare the climatic input data for the mapping of the MIDAS marginal land situation currently and also for the 2050 period (see also next section).

In addition to an update of the climate data, the soil input data was also exchanged using the more recent ISRIC- Soilgrids data from 2020. digital soil mapping using machine learning methods to map the spatial distribution of soil properties at a global scale. The SoilGrids prediction models are derived from 230,000 soil profile observations worldwide from the WoSIS database (Batjes et al. , 2020) and a series of environmental covariates mapped in 400 environmental layers from Earth Observation derived products and climate, land cover and terrain data. The data can be consulted (https://soilgrids.org/) and further details are provided at https://www.isric.org/explore/soilgrids .

The only threshold value that was changed was for soil fertility for the sub-factor (4b in Table 4) Low Soil organic carbon content (%). In MAGIC the threshold for severe was set at 0.75% SOC (1% for sub-severe) and the area detected as severe by this subfactor was extremely limited. In MIDAS we therefore consulted again the literature on at what SOC levels limitations for agronomic use are applicable. We conclude that there is certainly no uniform SOC threshold for which agronomic use is no longer possible. The literature is however consistent in that low SOC levels are constraining both yielding capacity and soil functions/soil health (e.g. Loveland & Web, 2003; Lal, 2020; Grilli et al., 2022). Yields start to level off at SOC levels below 2% in specific climate and soil types (Rubio et al, 2021; Lal, 2020 and Oldfield et al., 2020). Loveland & Web (2003) found in their literature review some evidence that if SOC is below 1% in a temperate climate zone, it may not be possible to obtain potential yields, even with additions of nitrogen fertilizers as the nitrogen is no longer mineralizable. Oelofse et al. (2015) found that a 0.85% SOC is the minimum level to sustain yields in Denmark.

Table 4 Overview of biophysical constraints and updated data used to map marginal lands in MIDAS

Cluster	Sub- factor	Description	Threshold for marginal lands used	Data sources used in MAGIC	Updates in MIDAS for current and for 2050
1. Adverse climate*	a. Low temperature*	Length of Growing Period: number of days with daily average temperature > 5°C (LGPt5) or Thermal-time sum (degree-days) for Growing Period defined by accumulated daily average temperature > 5°C.	LGPt ≤ 180 days Or Degree days <= 1500 days (<= 1575 = sub-severe)	CRU CY v. 3.24. Climatic Research Unit - CRU (1901-2015). Harris et al. (2014) doi:10.1002/joc.3711	CHELSA V2 (Climatologies at high resolution for the earth's land surface areas) (Karger et al., 2017). For current: Period climatic data 1981-2010, monthly, 1km resolution. For 2050: CMIP6 scenarios • GCM selection following ISIMIP3b (Inter-Sectoral Impact Model Intercomparison Project) • Scenario: SSP585, period: 2041-2070 • Monthly, *1km resolution*, bias corrected For further details see **Annex I.**
	b. Dryness*	Ratio of the annual precipitation (P) to the annual potential evapotranspiration (PET). Threshold limit: (P/PET ≤ 0.6)	P/PET ≤ 0.5 (< 0.6 = sub-severe)	CRU CY v. 3.24. Climatic Research Unit - CRU (1901-2015). Harris et al. (2014) doi:10.1002/joc.3711	
2. Excessive wetness*	a. Excess soil moisture*	Water content in the soil exceeds field capacity for at least 210 days (7 months)	210 days severe (190 days = sub-severe)	CRU CY v. 3.24. Climatic Research Unit - CRU (1901-2015). Harris et al. (2014) doi:10.1002/joc.3711	
	b. Limited soil drainage	Soils with high water tables throughout the year that have a lack of oxygen in the rooting zone, effectively limiting growth of crops	Gleysols, Histosols, Stagnosols, Planosol, Soils with primary qualifiers Histic, Gleyic and Stagnic and marshlands	ESDB v2.0: The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004	Updated ISRIC – SoilGrids (2020). Digital soil mapping using machine learning methods to map the spatial distribution of soil properties at a global scale https://www.isric.org/explore/soilgrids Batjes et al. (2020)
3. Adverse chemical conditions	a. Salinity (Ec)	Soils with high salinity content	Solonchaks and soils with a salic qualifier. For these salt level > 15 dS/m and more than 50% of the mapping unit area (sub-severe <50% of the mapping unit area)	Toth et al., (eds) (2008), Threats to soil quality in Europe. EUR 23438 EN - 2008 and https://esdac.jrc.ec.europa.eu/content/saline-and-sodic-soils-european-union	Identical to MAGIC
	b. Sodicity (Na – ESP)	Soils with high sodicity content	Solonetz, 'natric' soils, or 'Sodic' soils. Saturation with exchangeable sodium of more than 15% (ESP), and more than 50% of the mapping unit area (sub-severe <50% of the mapping unit area)	https://esdac.jrc.ec.europa.eu/content/saline-and-sodic-soils-european-union and ESDB v2.0: The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004	Identical to MAGIC
	c. Natural toxicity (e.g. Al, S)	Soils with high content of sulfur that have acidification potential upon drainage	Soils with Thionic qualifier	ESDB v2.0: The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004	Identical to MAGIC
	d. Toxicity by pollutants	Soils that have been polluted by man mostly through waste disposal or industrial processes	Not included	Not included	Not included: addressed in GOLD project. see: https://www.gold-h2020.eu/
	a. Soil reaction (pH)	Highly acidic and alkaline soils (0-30 cm)	Soils with pH below 4.5 or pH above 8 (at depth 0-30 cm)	Hengl, T., Mendes de Jesus, J., Heuvelink, G. B.M., Ruiperez Gonzalez, M., Kilibarda, M. et al. (2017)	Rules remain the same as in MAGIC, but input data updated with ISRIC – SoilGrids (2020). Digital soil mapping

Cluster	Sub- factor	Description	Threshold for marginal lands used	Data sources used in MAGIC	Updates in MIDAS for current and for 2050
4. Low soil fertility				SoilGrids250m: global gridded soil information based on Machine Learning. PLoS ONE 12(2): e0169748. doi:10.1371/journal.pone.0169748	using machine learning methods to map the spatial distribution of soil properties at a global scale https://www.isric.org/explore/soilgrids Batjes et al. (2020)
	b. Soil organic carbon (%)	Low organic carbon containing soils as an indicator for soils with low fertility and low biomass turnover (0-30 cm)	SOC % average of depth range 0-30 cm at In MAGIC <0.75% SOC = severe (<1% = sub-severe) **In MIDAS: <1 % SOC = severe (<1.25% = sub-severe)**	Hengl, T., Mendes de Jesus, J., Heuvelink, G. B.M., Ruiperez Gonzalez, M., Kilibarda, M. et al. (2017) SoilGrids250m: global gridded soil information based on Machine Learning. PLoS ONE 12(2): e0169748. doi:10.1371/journal.pone.0169748	Rules updated and input data updated with ISRIC – SoilGrids (2020). Digital soil mapping using machine learning methods to map the spatial distribution of soil properties at a global scale https://www.isric.org/explore/soilgrids Batjes et al. (2020) Thresholds are now: **<1 % SOC = severe (<1.25% = sub-severe)** The method to map is now as follows: The lowest estimated mean value for the SoilGrids for this depth was used including the substraction of the provided uncertainty layer. Values used following the new MIDAS thresholds are therefore the lowest predicted mean SOC values within the given uncertainty of the model output.
5. Limitations in rooting	a. Unfavourable soil texture	Texture class in half or more (cumulatively) of the 100 cm soil surface is sand, loamy sand defined as: silt% + (2 x clay%) ≤ 30%	Sand, loamy sand defined as: silt% + (2 x clay%) ≤ 30% (= Max 70% sand) (max 60% sand = sub-severe)	AGLIM1 : Code of the most important limitation to agricultural use of the STU https://esdac.jrc.ec.europa.eu/resource-type/european-soil-database-maps ESDB v2.0: The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004	Rules remain the same as in MAGIC, but input data updated with ISRIC – SoilGrids (2020). Digital soil mapping using machine learning methods to map the spatial distribution of soil properties at a global scale https://www.isric.org/explore/soilgrids Batjes et al. (2020)
	b. Coarse fragments 7 surface stones	> 35 cm (0-30 cm)	Course material At depth: 0-35 cm covering a surface of >35% and/or > 15% rock coverage (> 25% and/or > 10% respectively for sub-severe)	AGLIM1 : Code of the most important limitation to agricultural use of the STU https://esdac.jrc.ec.europa.eu/resource-type/european-soil-database-maps ESDB v2.0: The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004	Rules remain the same as in MAGIC, but input data updated with ISRIC – SoilGrids (2020). Digital soil mapping using machine learning methods to map the spatial distribution of soil properties at a global scale https://www.isric.org/explore/soilgrids Batjes et al. (2020)

Cluster	Sub- factor	Description	Threshold for marginal lands used	Data sources used in MAGIC	Updates in MIDAS for current and for 2050
	c. Organic soils	Organic matter ≥ 20%)	>= 20% organic matter = Histosols	ESDB v2.0: The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004	Rules remain the same as in MAGIC, but input data updated with updated ISRIC – SoilGrids (2020). Digital soil mapping using machine learning methods to map the spatial distribution of soil properties at a global scale https://www.isric.org/explore/soilgrids Batjes et al. (2020)
	d. Shallow rooting depth	Depth (cm) from soil surface to coherent hard rock or hard pan	< 30 cm rooting depth possible. Selected soils for mapping: Leptosols, Albeluvisols, Lithic, Petrocalcic, Fragipans, Duripans, Petroferric	AGLIM1 : Code of the most important limitation to agricultural use of the STU https://esdac.jrc.ec.europa.eu/resource-type/european-soil-database-maps ESDB v2.0: The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004	Rules remain the same as in MAGIC, but input data updated with updated ISRIC – SoilGrids (2020). Digital soil mapping using machine learning methods to map the spatial distribution of soil properties at a global scale https://www.isric.org/explore/soilgrids Batjes et al. (2020)
e. Adverse terrain conditions*	a. Steep slope	Change of elevation with respect to planimetric distance (%).	>80% of area has a slope of > 15% slope (> 60% of the area has a slope of >15% slope = sub-severe)	European Digital Elevation Model (EU-DEM), version 1.1	Rules remain the same as in MAGIC, but input data updated with latest EURO-DEM (EUROSTAT GISCO https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/elevation/eu-dem). DEM is static for 2050
	a. Flood risk*	Risk of flooding in relation to risk of damage to the field and to crops during the growing season	> 2 m flood in 2yrs return time (>1-2 m flood in 2 yr return time =sub-severe)	JRC_Lisflood_2025 2 Years Return rate. Dankers, R. and L. C. D. Feyen (2009). "Flood hazard in Europe in an ensemble of regional climate scenarios." Journal of Geophysical Research: Atmospheres 114(D16). DOI 10.1029/2008JD011523	No update. The most recent JRC Flood Risk Hazard Maps from Dottori et al 2022 were not used for two reasons: - They do not depict reality managed (diked) floodplain areas like the Netherlands. They also acknowledge this in their paper where they state that the maps *" overestimate flood-prone areas with below 1-in-100-year flood probabilities"* - They do not provide flood risk with a short return period (<4 years) which is of interest for agricultural practices. The minimum provided is 10 years

**Clusters and sub-factors that are affected by climate change and that will be determining the shifts in marginal lands between 2023 and 2050*

At a global level Lal et al. (2015) found that SOC levels between 1% to 1.5% are critical to maintain the restorative capacity of soils. For the Mediterranean Grilli et al. (2021) examined the relationship between SOC concentrations and other soil properties in the topsoil in 38 sites in Portugal, Italy and Spain prone to desertification. The study defined 2% SOC as a critical value below which important soil function loss takes place. The technical working group for Soil Organic Carbon under the Thematic Strategy for Soil Protection (Camp et al., 2004) mention a 1.7% SOC (3.4% SOM) threshold as a critical level below which restoration of SOC should start to prevent further degradation by erosion and towards desertification.

From this small literature review we conclude that there is clearly no one uniform critical SOC level for soil health and agronomic use, but that this ranges between 0.5% to 2% SOC and that this is enough motivation to increase the MIDAS marginal land sub-factor for low soil fertility from 0.75% SOC (used in MAGIC) to 1% SOC. This does not mean that all lands with below 1% SOC will be mapped as marginal, because like in MAGIC a correction is applied for human management. There are lands that have low SOC levels, but these have been neutralised by human interference, making them well suited for normal and even high productive agriculture. In the case of soils with low SOC levels this is seen a lot on the poor sandy soils of Flanders (De Kempen region) and of the southern and eastern Netherlands, where high manure application supports high yields (of e.g. forage maize and grass).

For the mapping of low soil organic carbon levels (see 4b in Table 4) in MIDAS the thresholds were changed, but also the input data used to map the marginal lands was updated with the more recent ISRIC SoilGrid (2020). Also for the mapping uncertainty in the SOC data was addressed by choosing the lowest estimated mean value for SOC level from the SoilGrids including the substraction of the provided uncertainty layer. Values used following the new MIDAS thresholds are therefore the lowest predicted mean SOC values within the given uncertainty of the model output.

Pairwise combinations of sub-severe single factors in MIDAS

The approach to mapping the pairwise combinations was similar to the one applied in MAGIC and explained in Table 2 in section 2.1. The only difference with MAGIC is that in MIDAS the data of many sub-indicators were updated and most importantly two additional pairwise combinations have been added:

- Low soil fertility and slope
- Low soil fertility and dryness

This implies that if low soil fertility is sub-severe (so 1%<SOC<1.25%) and it occurs in combination with sub-sever classes in slope (> 60% of the area has a slope of >15% slope) and/or in dryness (1500<degree days <= 1575) they jointly become severe, so marginal (see also Table 2).

These new pairwise combinations are not based on Terres et al. (2014) but are based on Hijbeek et al. (2017) who show under what conditions SOC/SOM levels can be considered critical in view of the productive capacity of the soil. The key factors identified are slope, soil texture (i.e. clay content), climate and land use. The steeper the slope the more critical low SOC levels become. The same applies for dry climates where large water deficiencies make low SOC levels more critical (Hijbeek et al., 2017; Grilli et al., 2021; Camp et al., 2004). In MIDAS there were also sub-severe levels identified for slope and dryness which form the severe score in a pairwise combination.

2.3 Mapping Marginal lands in 2050 in MIDAS

For 2050 the change in marginal land location is determined by changes in climate. All factors making up marginal lands influenced by climate will experience shifts. In Table 4 all clusters and sub-factors that were adapted for climate change effects towards 2050 are marked with *. These factors include:

1.Adverse climate
- a. Low temperature
- b. Dryness

2.Excessive wetness
- c. Excess soil moisture

6.Adverse terrain conditions
- p. Flood risk

In order to understand the implications of climate change on these factors again the CHELSA climatologies at high resolution for land surface data were used (Karger et al., 2017) providing modelled climate change predictions for most important monthly 1 km climate variables for the period 2041-2070. The climate variables come from different Global Climate Models (GCMs) that have simulated the most recent CMIP6 (Coupled Model Intercomparison Project Phase 6), designed to test and compare specific aspects of climate models (GCMs). The simulated climate scenario used for the mapping of marginal lands in 2050 is the most extreme SSP585. This SSP5 scenario is the high end or upper boundary of plausible future pathways, with emissions high enough to produce the 8.5 W/m2 level of forcing in 2100. This high emission scenario is often referred to as the 'business as usual' as it is the likely outcome if society does not make concerted action to considerably decline GHG emissions.

The factors that were derived from CHELSA for 2050 were:

- Daily mean/max./min. air temperature.
- Precipitation; amount per month
- GGD 5°C: heat sum of all days above the 5°C temp. accumulated over 1 year

These factors were further converted in a pre-processing procedure (see for further details Annex I) in the 4 sub-indicators of marginal land already summarized in the former.

A choice had to be made about which Global Climate Models (GCMs) output was to be used. In CHELSA variables from 5 GCM models are available: GFDL-ESM4, UKESM1-0-LL, MPI-ESM1-2-HR, IPSL-CM6A-LR, MRI-ESM2-0. The first GFDL model is regarded as the most solid model, so output of this model always needs to be used. It was decided that for the marginal land mapping 4 sets of data will be produced:

1. GFDL result,
2. 5 models mean,
3. 5 models min,
4. 5 models max.

The marginal lands will be mapped according to the GFDL variables and the 5 models' average. The models min and max can be used for sensitivity analysis of the results. For further details on the pre-processing of these climate variables into sub-factors see also Annex I.

3 Marginal lands 2020 and 2050

3.1 Marginal lands 2020

The mapped result of the updated MIDAS marginal land map is summarized in Table 5 by country. The area share is like in MAGIC, expressed in relation to the historic 'agricultural mask' that consists of all agricultural and semi-natural land cover classes between 1990-2018 (see Annex II).

Table 5 Current land area absolute (km2) and relative (%/ MAGIC historic agricultural land) coverage* by 6 clusters of biophysical constraints making up marginal lands (mapped as severe and severe by pair-wise combination)

km2	1 Climate	2 Wetness	3 Fertility	4 Chemical	5 Rooting	6 Terrain	total marginal (km2)	Total marginal %	not-marginal or sub-severe
Austria	10016	7137	156	260	5433	10568	15684	45%	19191
Belgium	259	140	149	0	118	0	513	3%	16801
Bulgaria	1409	25	139	820	2544	2921	6618	11%	55142
Croatia	86	5340	41	0	4103	869	7958	31%	17719
Czech Rep.	1084	1303	200	52	63	176	2551	6%	42646
Denmark	1	2670	40	0	5048	0	7729	24%	24687
Estonia	4551	5337	14	0	307	0	8159	56%	6495
Finland	34729	9907	12432	0	3963	39	34898	100%	158
France	10562	22456	350	4589	21546	13952	49768	14%	297079
Germany	2699	22528	2418	9	15321	1077	38879	19%	167265
Greece	3384	37	3191	1345	22585	18774	36169	44%	46822
Hungary	0	2995	1365	6076	7113	8	14641	23%	48839
Ireland.	1832	29770	1159	0	3841	642	30322	62%	18762
Italy	7386	4508	2641	1887	10893	20776	34052	19%	140881
Latvia	624	3296	17	0	1266	0	5095	20%	20602
Lithuania	57	1287	361	0	9330	0	10814	28%	27459
Luxembourg	0	0	3	0	127	1	131	9%	1269
Netherlands	0	1739	196	0	1219	0	3061	12%	21800
Poland	767	10844	6176	0	16216	258	30778	17%	153640
Portugal	749	1485	264	1369	9200	2681	12178	24%	39099
Romania	5102	5993	432	5238	36587	6410	42818	30%	98689
Slovakia	1240	467	94	527	3569	890	5315	23%	18210
Slovenia	291	2656	10	22	1972	979	3396	47%	3871
Spain	71283	16703	86341	3396	88301	30522	185854	54%	156850
Sweden	42440	24050	15672	0	6911	2851	48891	71%	20074
*UK****	*47097*	*79570*	22294	*0*	*27455*	*6399*	*96365*	58%	*71051*
Total	**247648**	**262243**	**156155**	**25590**	**305031**	**120793**	**732637**	**32%**	**1535101**

** Area refers to total marginal land area in EU+UK (minus Malta & Cyprus) that can be regarded 'agricultural' as it has been in continuous or discontinuous agricultural use (according to Corine Land Cover (CLC)) between 1990 and 2018) (See Annex II)*

***Total marginal land is not equal to the total of all cells per country because the 6 marginal limitations can occur simultaneously in the same location (e.g. steep slope and rooting limitations etc.)*

**** UK is kept in this table for comparison reasons with the original marginal land mapping exercise*

Table 6 Current land area absolute (km2) and relative (%/agricultural land) coverage* by 6 clusters of biophysical constraints making up marginal lands (mapped as severe and severe by pair-wise combination) per environmental region

km2	1 Climate	2 Wetness	3 Fertility	4 Chemical	5 Rooting	6 Terrain	total marginal	%	not-marginal or sub-severe
Alpine	33311	26608	331	27	27133	32002	50985	69%	22979
Atlantic	49881	134401	25895	3364	66672	17580	185346	29%	464703
Continental	7991	46515	10350	12931	74199	8700	136264	20%	556356
Mediterranean.	74078	10153	91470	9268	114964	59554	251641	38%	417998
North	82387	44566	28109	0	22063	2957	108401	60%	73065
Total (EU+UK)*	**247648**	**262243**	**156155**	**25590**	**305031**	**120793**	**732637**	**32%**	**1535101**

*EU+UK minus Malta and Cyprus

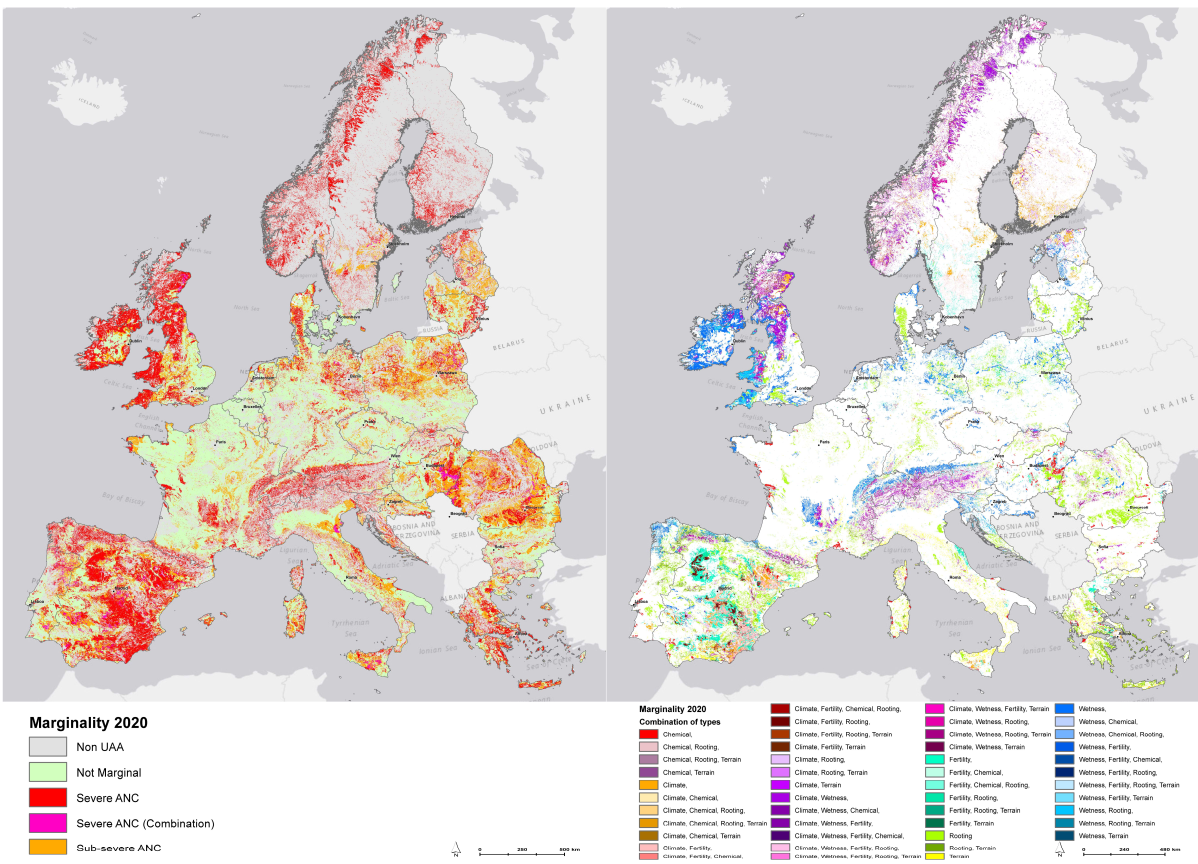

Figure 1 MIDAS marginal area resulting from the combination of 6 clusters of biophysical constraints (mapped as severe and severe by pair-wise combination) for 2020 (left severity, right type of marginality factor)

On average in the total EU & UK there is more then 732,637 km2 (>74 million ha) of marginal lands which covers 32% of the agricultural area mask used in MAGIC (see Annex II). Countries with the largest absolute area of marginal lands are Finland, Sweden, Ireland, Estonia, Spain and UK. Small area shares of marginal lands are found in Belgium, Czech republic, Luxembourg, Bulgaria, Netherlands and France.

The most dominant marginal factors are rooting, wetness and climate. Rooting is a cluster of a wide range of soil limiting factors and it is therefore not surprising that is covers a large area. Also, the climate limitation of low temperature leading to a short growing season covers a large area in Europe. The latter is responsible together with the wetness limitation for the high marginal land share in the Environmental region North (see Table 6 and Figure 1 and Figure 2).

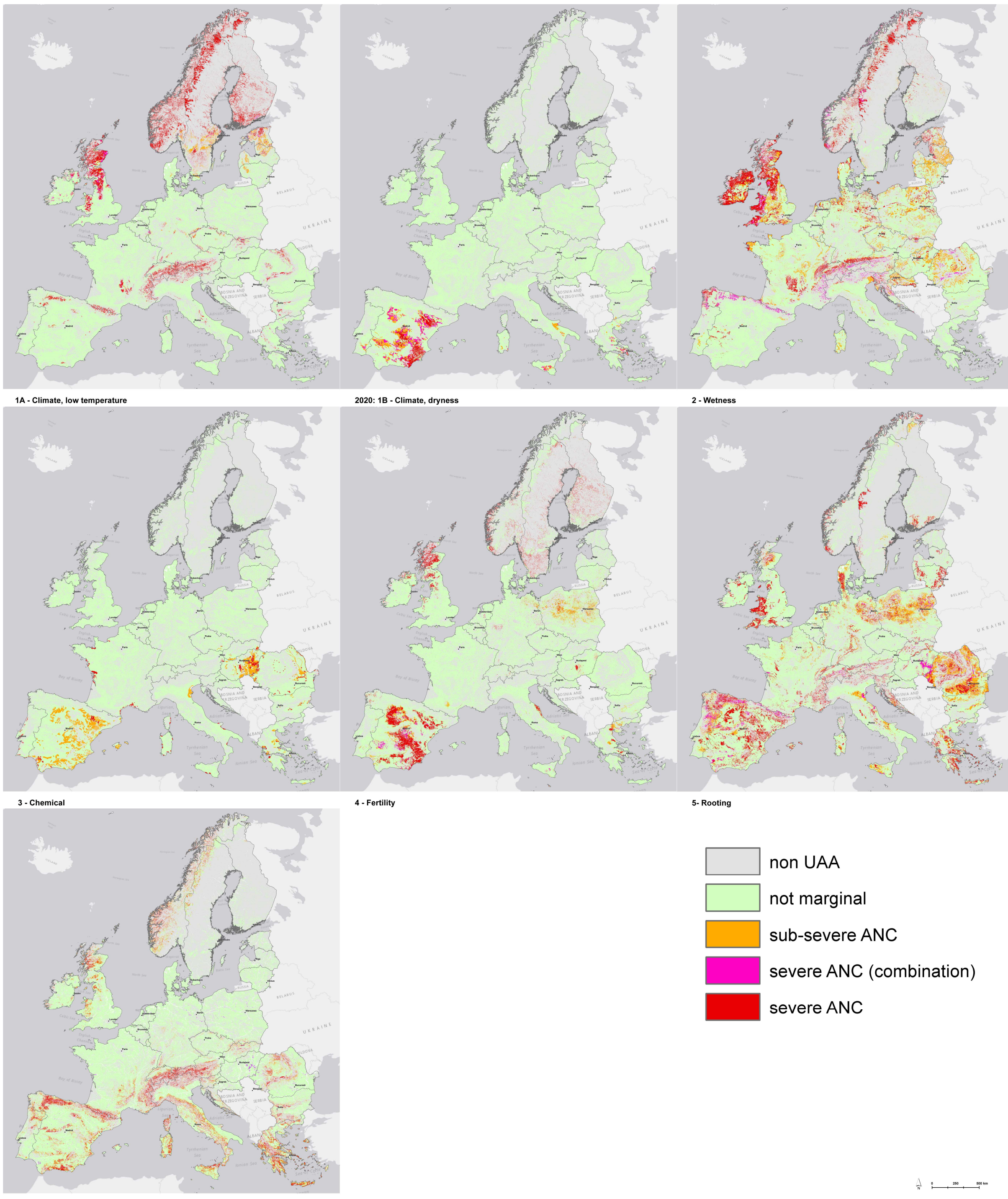

Figure 2 Maps of the 6 clusters of biophysical constraints making up marginal lands in 2020 (mapped as severe and severe by pair-wise combination). The cluster climate is split in 2 maps, one for temperature (short growing season) and 1 for dryness.

The rooting limitation is more evenly spread over all environmental regions. The continental region has the smallest marginal land share and the largest limiting factor is rooting. In comparison to the other environmental regions the Continental region has the biggest absolute and relative area with chemical limitations. In the Atlantic region the limiting factors covering the largest area are wetness and rooting, but overall, this his region has a low marginal land share. The largest marginal land area in absolute terms, making up more than 25 million hectares is in the Mediterranean region. The marginal land share of this region is 38% which is below the share in the North and the Alpine region, but is high in comparison to the Atlantic and Continental regions. The most dominant marginal factors in the Mediterranean are rooting and fertility but it is also the region with the largest area in the terrain limiting factor.

3.2 Marginal lands mapped in MAGIC and in MIDAS

As explained in chapter 2, several updates were made in the marginal land mapping in MIDAS as compared to the original MAGIC marginal land mapping. The mapped results for MIDAS are compared at the total EU+UK level in Figure 3. The differences in total area are displayed for the 6 clusters of biophysical constraints. In total the area mapped as marginal increased in MIDAS by 38,317 km2 which is a relative increase of 5.5%. In MAGIC it covers 29% and in MIDAS 32% of the historic MAGIC agricultural mask (see Annex II). The largest increase in area because of updated data are in the wetness and the fertility cluster (Figure 3). Wetness area increases are caused by updated climatic input data, while for rooting this can be most strongly explained by the shift of the SOC % limit in MIDAS to 1% for severe and 1.25% for sub-severe (in MAGIC it was 0.75% severe and 1% sub-severe) and the addition of pairwise combinations of this factor with slope and dryness in the sub-severe class. There were also decreases in marginal land area in the MIDAS map in relation to the climate, terrain and chemical clusters. These were not caused by changes in limits but by updates in the SoilGrid data used.

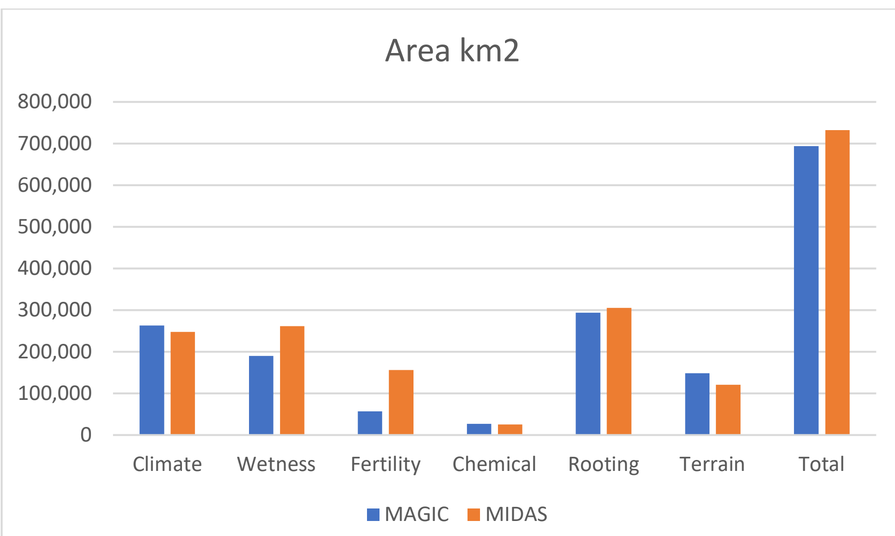

Figure 3 Marginal lands in 2020 (mapped as severe and severe by pair-wise combination) in MAGIC and in MIDAS ((EU+UK minus Malta and Cyprus)

The shifts in mapped marginal area have the largest consequences for marginal area share in countries like Romania, Denmark, Ireland, Belgium, Latvia, Luxembourg either increasing or decreasing relatively. In terms of absolute marginal land area changes Spain, France, UK, Romania and Greece show large shifts (Figure 4).

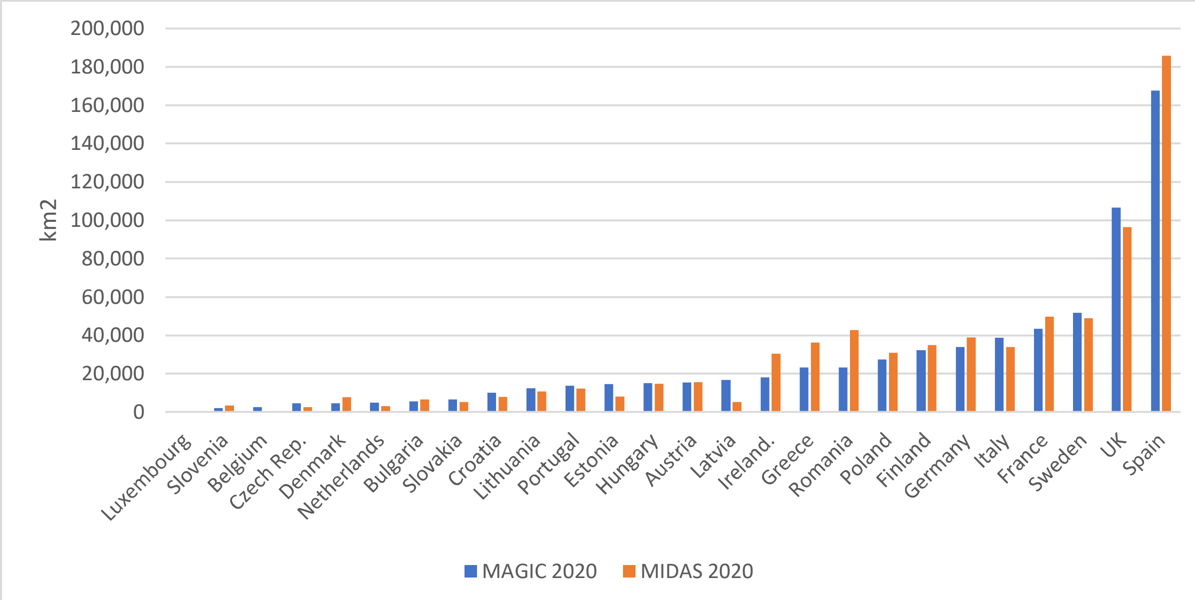

Figure 4 Marginal lands in 2020 (mapped as severe and severe by pair-wise combination) in MAGIC and in MIDAS per country (EU+UK minus Malta and Cyprus)

3.3 Expectations for Marginal lands in 2050

In Chapter 2 it is explained that for 2050 the change in marginal land location is determined by changes in climate. All factors making up marginal lands influenced by climate will change towards 2050.

Table 7 Expected future (2050) land area (km2) coverage* by 6 clusters of biophysical constraints making up marginal lands (mapped as severe and severe by pair-wise combination)

km2	1 Climate	2 Wetness	3 Fertility	4 Chemical	5 Rooting	6 Terrain	total marginal	%	not-marginal or sub-severe
Austria	7643	6613	156	260	5433	10568	15684	43%	20014
Belgium	0	14	149	0	118	0	513	2%	17037
Bulgaria	3382	0	385	820	2544	2921	6618	14%	53202
Croatia	0	4472	41	0	4103	869	7958	29%	18204
Czech Rep.	52	1221	200	52	63	176	2551	4%	43498
Denmark	0	2247	40	0	5048	0	7729	23%	25104
Estonia	0	5313	14	0	307	0	8159	38%	9028
Finland	8954	11255	12432	0	3963	39	34898	70%	10554
France	4043	16260	350	4589	21546	13952	49768	13%	303054
Germany	461	21612	2418	9	15321	1077	38879	18%	168986
Greece	7945	12	3914	1345	22585	18774	36169	47%	44054
Hungary	0	2995	1365	6076	7113	8	14641	23%	48839
Irish Rep.	99	21139	1159	0	3841	642	30322	44%	27481
Italy	11210	3983	2729	1887	10893	20776	34052	22%	136805
Latvia	0	3295	17	0	1266	0	5095	18%	21121
Lithuania	0	1286	361	0	9330	0	10814	28%	27460
Luxembourg	0	0	3	0	127	1	131	9%	1269
Netherlands	0	1423	196	0	1219	0	3061	11%	22116
Poland	64	10625	6176	0	16216	258	30778	17%	153892
Portugal	4713	440	596	1369	9200	2681	12178	28%	36889
Romania	10540	4853	476	5238	36587	6410	42818	34%	92913

km2	1 Climate	2 Wetness	3 Fertility	4 Chemical	5 Rooting	6 Terrain	total marginal	%	not-marginal or sub-severe
Slovakia	353	405	94	527	3569	890	5315	20%	18728
Slovenia	164	1893	10	22	1972	979	3396	41%	4292
Spain	135086	8075	96941	3396	88301	30522	185854	64%	124646
Sweden	31504	24131	15672	0	6911	2851	48891	64%	24653
*UK****	*10122*	*69578*	*22294*	*0*	*27455*	*6399*	*96365*	*51%*	*82433*
Total	**236335**	**223140**	**168188**	**25590**	**305031**	**120793**	**731466**	**32%**	**1536272**

** Area refers to total marginal land area in Europe that can be regarded 'agricultural' as it has been in continuous or discontinuous agricultural use (according to Corine Land Cover (CLC)) between 1990 and 2018).*
***Total marginal land is not equal to the total of all cells per country because the 6 marginal limitations can occur simultaneously in the same location (e.g. steep slope and rooting limitations etc.)*
**** UK is kept in this table for comparison reasons with the original marginal land mapping exercise*

Table 8 Expected future (2050) land area (km2) coverage* by 6 clusters of biophysical constraints making up marginal lands (mapped as severe and severe by pair-wise combination) per environmental region

km2	1 Climate	2 Wetness	3 Fertility	4 Chemical	5 Rooting	6 Terrain	total marginal	%	not-marginal
Alpine	18879	20002	331	27	27133	32002	46064	62%	27900
Atlantic	10254	105656	25895	3364	66672	17580	159536	25%	490513
Continental	12808	44515	10593	12931	74199	8700	141095	20%	551525
Mediterranean	153862	6962	103260	9268	114964	59554	294333	44%	375306
North	40532	46005	28109	0	22063	2957	90438	50%	91028
Total	**236335**	**223140**	**168188**	**25590**	**305031**	**120793**	**731466**	**32%**	**1536272**

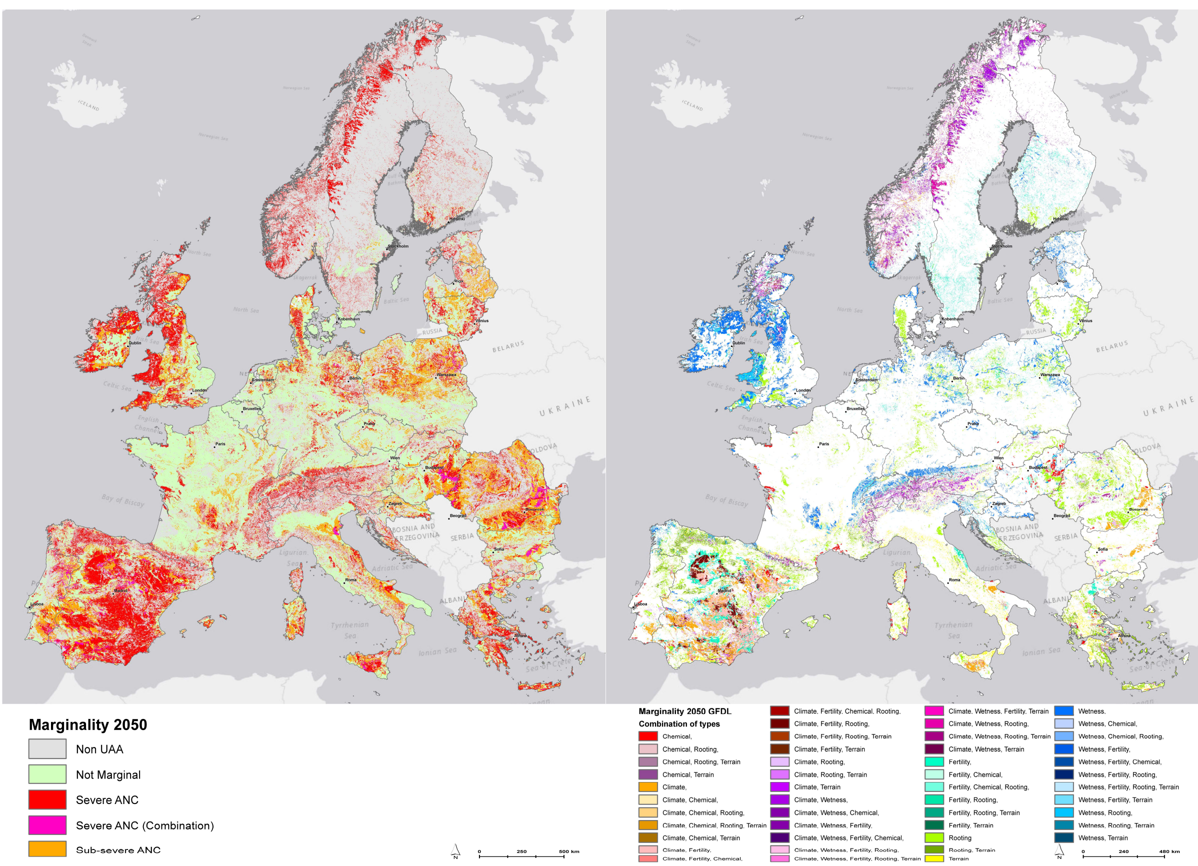

Figure 5 MIDAS marginal area resulting from the combination of 6 clusters of biophysical constraints (mapped as severe and severe by pair-wise combination) for 2050 (left severity, right type of marginality factor)

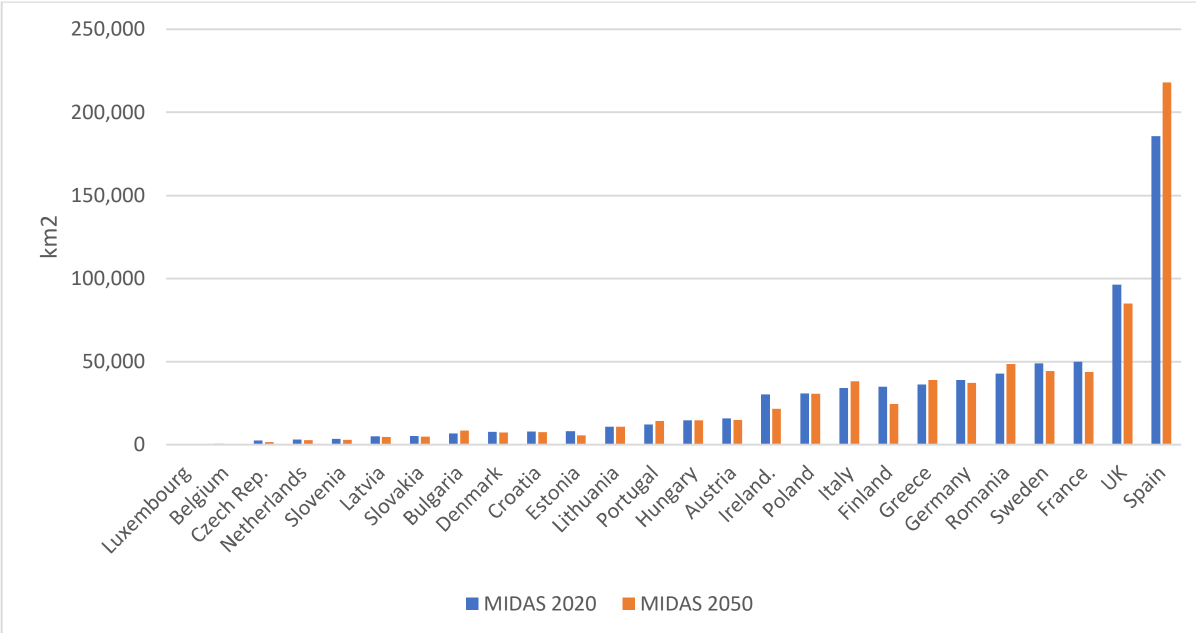

Figure 6 Change in MIDAS marginal land area between 2020 and 2050 per country

The resulting 2050 marginal land mapping is summarized for EU+UK per country in Table 7 and per Environmental region in Table 8. In both situations to calculate the area shares the broader MAGIC historical agricultural mask was used (see Annex II). Interestingly, the total area share at EU+UK level remains at 32% between 2020 and 2050. However, shifts in marginal land area between 2020 and 2050 within countries and Environmental regions can be big however (see Figure 6). The largest declines in marginal lands between 2020 and 2050 will be seen in Finland, UK, Ireland, Sweden, France, Estonia and Germany. The largest absolute increases will be seen in Spain, Romania, Italy, Greece, Portugal and Bulgaria. What is exactly behind the shifts in marginal land will be discussed further in next section.

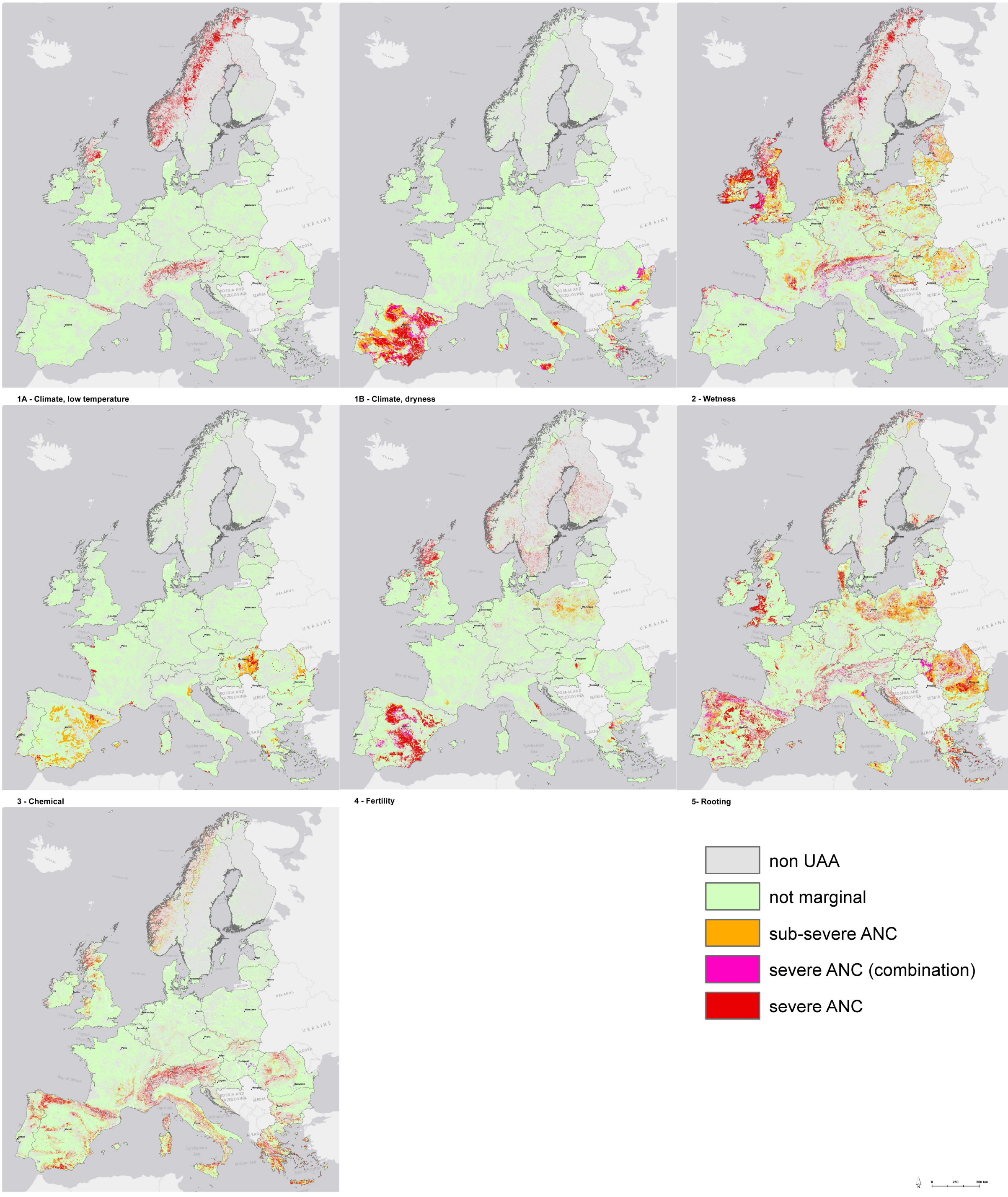

Figure 7 Maps of the 6 clusters of biophysical constraints making up marginal lands in 2050 (mapped as severe and severe by pair-wise combination). The cluster climate is split in 2 maps, one for temperature (short growing season) and 1 for dryness.

3.4 Shifts in Marginal lands between 2020 and 2050 explained

In this section, we perform statistical analyses using the agricultural CLC2018 mask, deeming it the most suitable starting point for the within MIDAS comparison of shifts in marginal land between 2020 and 2050 (see Annex II). So, this is a agricultural land mask for 2018, while the one used in MAGIC and also applied in the former sections, takes the wider historical agricultural land mask covering all land that was once or still agricultural between 1990-2018. For shifts between 2020 and 2050 it is logical to use a stable baseline of agricultural land which is the 2018 situation.

The total area of EU27+ UK classified as marginal land (focus on agricultural land 2018) is decreasing in the period 2020-2050 with 0.3% (Table 11). The total area of agricultural land mapped as marginal land is slightly decreasing with 6,385km^2 from 513,521km^2 to 507,136km^2. The decrease is for all marginal land types except the ones grouped under the biophysical constraints climate and terrain.

The changes for the total EU and per Environmental regions are presented in Table 9 and Table 10. From the current total agricultural land (taken from Corine Land Cover 2018 (CLC 2018)) 90.9% is not changing in marginality nor in one or in pairwise combinations of constraints. Only for 4.3% of the total agricultural land the marginality land type will change towards 2050 (see

Table 10). From the 2.6% of agricultural land that was marginal in 2020 the climate or wetness constraints disappears by 2050. New marginal lands in 2050 are foreseen for 2.2% of the total agricultural land and are due to climate (37,568km^2), wetness (542km^2) or fertility (6,209km^2) constraints.

Table 9 Land area (km2) making up marginal lands (mapped as severe and severe by pair-wise combination) for 2020 and 2050 for EU27 + UK[1,2] and per Environmental zone.

Marginal km2	2020	2050	difference	identical type 2020 - 2050	shift in type 2020 - 2050	only marginal in 2020	only marginal in 2050
EU-27+UK	513521	507136	-6385	376548	86269	50704	44319
North	71069	53210	-17859	29482	23728	17859	0
Alpine	21130	16745	-4385	11754	4948	4428	43
Continental	127333	132548	5215	118710	5677	2946	8161
Atlantic	136486	113105	-23381	95378	17469	23639	258
Mediterranean	157503	191528	34025	121224	34447	1832	35857

[1] Total agricultural area based on CLC2018 (CLC level 1 agricultural areas) for EU27 + UK minus Cyprus and Malta.

[2] Surface areas per group of constraints is calculated as a summation. E.g. the current climate area is a summation of all areas where climate is a constraint without taking into account if any other constraint plays a role, thereafter the current wetness area is a summation of all areas where wetness is a constraint (and climate not) without taking into account if fertility, chemical, rooting and/or terrain constraints play a role.

Table 10 Land area share (%/agricultural area CLC 2018) making up marginal lands (mapped as severe and severe by pair-wise combination) for 2020 and 2050 for EU27 + UK[1,2] and per Environmental zone.

Marginal % / agricultural land	2020	2050	difference	identical type 2020 - 2050	shift in type 2020 - 2050	only marginal in 2020	only marginal in 2050
EU-28	25.9%	25.5%	-0.3%	19.0%	4.3%	2.6%	2.2%
North	49.2%	36.9%	-12.4%	20.4%	16.4%	12.4%	0%
Alpine	48.6%	38.5%	-10.1%	27.0%	11.4%	10.2%	0.1%
Continental	18.7%	19.5%	0.8%	17.5%	0.8%	0.4%	1.2%
Atlantic	22.8%	18.9%	-3.9%	15.9%	2.9%	3.9%	0.0%
Mediterranean	30.4%	36.9%	6.6%	23.4%	6.6%	0.4%	6.9%

In three of the five environmental regions there will be a net decline in marginal lands towards 2050 and in the other two regions there is a net increase expected (Table 9). Overall, the largest decline in marginal lands between 2020 and 2050 will be seen in the North, while the largest increases will be in the Mediterranean region. In the North 12.4% of the agricultural land will convert from marginal in 2020 to non-marginal in 2050 (see Table 10).

In the following it is discussed how marginality within the EU+UK is changing in the period 2020-2050. For each of the environmental zones North, Alpine, Continental, Atlantic and Mediterranean the changes in marginality and their main constraints are presented in relation to the current agricultural area (CLC 2018). It will give more insight why and where in Europe marginality is declining while in other parts marginality is increasing under influence of a changing climate.

Table 11. Land area share (km² and %/agricultural area CLC 2018) of total and for 6 clusters of biophysical constraints making up marginal lands (mapped as severe and severe by pair-wise combination) for 2020 and 2050 for EU + UK[1,2].

km2	2020	2050	difference	identical type 2020 - 2050	shift in type 2020 - 2050	only marginal in 2020	only marginal in 2050
CurrentClimate	129448	130287	839	55797	44578	29073	37568
CurrentWetness	148428	143912	-4516	121609	5188	21631	542
CurrentFertility	61858	61377	-481	39533	22325	0	6209
CurrentChemical	20627	17870	-2757	17861	2766	0	0
CurrentRooting	130189	129657	-532	119639	10550	0	0
CurrentTerrain	22971	24033	1062	22109	862	0	0
Marginal total	513521	507136	-6385	376548	86269	50704	44319
Not Marginal	1471882	1478267	6385	1427563			

%	2020	2050	difference	identical type 2020 - 2050	shift in type 2020 - 2050	only marginal in 2020	only marginal in 2050
CurrentClimate	6.5%	6.6%	0.0%	2.8%	2.2%	1.5%	1.9%
CurrentWetness	7.5%	7.2%	-0.2%	6.1%	0.3%	1.1%	0.0%
CurrentFertility	3.1%	3.1%	0.0%	2.0%	1.1%	0.0%	0.3%
CurrentChemical	1.0%	0.9%	-0.1%	0.9%	0.1%	0.0%	0.0%
CurrentRooting	6.6%	6.5%	0.0%	6.0%	0.5%	0.0%	0.0%
CurrentTerrain	1.2%	1.2%	0.1%	1.1%	0.0%	0.0%	0.0%
Marginal total	25.9%	25.5%	-0.3%	19.0%	4.3%	2.6%	2.2%
Not Marginal	74.1%	74.5%	0.3%	71.9%			

[1] Total agricultural area based on CLC2018 (CLC level 1 agricultural areas) for EU27 + UK minus Cyprus and Malta.
[2] Surface areas per group of constraints is calculated as a summation. E.g. the current climate area is a summation of all areas where climate is a constraint without taking into account if any other constraint plays a role, thereafter the current wetness area is a summation of all areas where wetness is a constraint (and climate not) without taking into account if fertility, chemical, rooting and/or terrain constraints play a role.

At the **whole EU+UK level** net shifts ensure that the marginal land share of 26% of agricultural area in 2020 remains at 26% in 2050. The constraint types that show the largest shifts are logically climate, but also fertility and rooting (Table 11). The increase in fertility limitations (by 22,325 km^2) is caused by the pairwise combination of low SOC % in combination with dryness and this pairwise combination also leads to a net increase in area by 2050. The shift towards more rooting limitations (by 10,550 km^2) is caused by the pairwise combination of rooting depth with dryness or with excessive wetness. The latter situation does not lead to a net increase of the area with these pairwise constraints by 2050, as in some places it increases while in other places it decreases. The other shifts in constraints for wetness, chemical and terrain constraints are relatively modest and through pairwise combinations cause a net decline in marginal lands.

If we focus on the marginal land changes in the **environmental region of North** we can see that the total area classified as marginal land (focus on agricultural land 2018) is decreasing significantly in the period 2020-2050 with 12.4% (Table 12). The total area of agricultural land that is mapped as marginal decreases by 17,859km^2 from 71,069km^2 to 53,210km^2. The most important reason for this decrease is an increase in length of growing season caused by higher temperatures decrease in precipitation expected under influence of climate change by 2050. The area of land mapped as marginal due to the constraint grouped under wetness also declines. The chemical and terrain constraints are not present in the North both in 2020 and 2050. Only 71.2% of the total agricultural land is not changing in marginality nor in one or in a pairwise combination of constraints. For 16.4% of the total agricultural land the marginality land type changed. From the 12.4% of agricultural land that was only marginal in 2020 the climate (and to limited extend wetness) constraints (17,288km^2) are released. New marginal land in 2050 is not appearing in the environmental zone North.

Table 12. Land area share (km^2 and %/agricultural area CLC 2018) of total and for 6 clusters of biophysical constraints making up marginal lands (mapped as severe and severe by pair-wise combination) for 2020 and 2050 for Environmental region North[1,2].

km2	2020	2050	difference	Identical type 2020 - 2050	shift in type 2020 - 2050	only marginal in 2020	only marginal in 2050
CurrentClimate	45366	3859	-41507	3859	23685	17822	0
CurrentWetness	8533	13552	5019	8457	39	37	0
CurrentFertility	5451	20289	14838	5447	4	0	0
CurrentChemical	0	0	0	0	0	0	0
CurrentRooting	11719	15510	3791	11719	0	0	0
CurrentTerrain	0	0	0	0	0	0	0
Marginal total	71069	53210	-17859	29482	23728	17859	0
Not Marginal	73242	91101	17859	73242			

%	2020	2050	difference	identical type 2020 - 2050	shift in type 2020 - 2050	only marginal in 2020	only marginal in 2050
CurrentClimate	31.4%	2.7%	-28.8%	2.7%	16.4%	12.3%	0.0%
CurrentWetness	5.9%	9.4%	3.5%	5.9%	0.0%	0.0%	0.0%
CurrentFertility	3.8%	14.1%	10.3%	3.8%	0.0%	0.0%	0.0%
CurrentChemical	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CurrentRooting	8.1%	10.7%	2.6%	8.1%	0.0%	0.0%	0.0%
CurrentTerrain	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Marginal total	49.2%	36.9%	-12.4%	20.4%	16.4%	12.4%	0.0%
Not Marginal	50.8%	63.1%	12.4%	50.8%			

[1] Total agricultural area based on CLC2018 (CLC level 1 agricultural areas) for EU27 + UK minus Cyprus and Malta.
[2] Surface areas per group of constraints is calculated as a summation. E.g. the current climate area is a summation of all areas where climate is a constraint without taking into account if any other constraint plays a role, thereafter the current wetness area is a summation of all areas where wetness is a constraint (and climate not) without taking into account if fertility, chemical, rooting and/or terrain constraints play a role.

The total area of **environmental region Alpine** classified as marginal land (focus on agricultural land 2018) is also decreasing in the period 2020-2050 with 10.1% (Table 13). The decrease is only for marginal land types where climate or wetness are a biophysical constraint either alone or in a pair-wise combination like for fertility and wetness. The total area of agricultural land that is mapped as marginal decreases with 4,385km^2 from 21,130km^2 to 16,745km^2. The chemical constraints are not applicable in the Alpine environmental region. From the total agricultural land 78.3% is not changing in marginality nor in one or a pairwise combination of constraints. For 11.4% of the total agricultural land the marginality land type changes towards 2050. From the 10.2% of agricultural land that was only marginal in 2020 the climate or wetness constraints decline. New marginal land in 2050 is almost absent and only appearing due to fact that an area of 42km^2, which is 0.1% of total agricultural land, is meeting the wetness constraints by 2050.

Table 13. Land area share (km^2 and %/agricultural area CLC 2018) of total and for 6 clusters of biophysical constraints making up marginal lands (mapped as severe and severe by pair-wise combination) for 2020 and 2050 for Environmental region Alpine[1,2].

km2	2020	2050	difference	identical type 2020 - 2050	shift in type 2020 - 2050	only marginal in 2020	only marginal in 2050
CurrentClimate	7342	460	-6882	457	4389	2496	1
CurrentWetness	7736	6884	-852	5252	552	1932	42
CurrentFertility	72	142	70	71	1	0	0
CurrentChemical	27	27	0	27	0	0	0
CurrentRooting	3229	4993	1764	3225	4	0	0
CurrentTerrain	2724	4239	1515	2722	2	0	0
Marginal total	21130	16745	-4385	11754	4948	4428	43
Not Marginal	22383	26768	4385	22340			

%	2020	2050	difference	identical type 2020 - 2050	shift in type 2020 - 2050	only marginal in 2020	only marginal in 2050
CurrentClimate	16.9%	1.1%	-15.8%	1.1%	10.1%	5.7%	0.0%
CurrentWetness	17.8%	15.8%	-2.0%	12.1%	1.3%	4.4%	0.1%
CurrentFertility	0.2%	0.3%	0.2%	0.2%	0.0%	0.0%	0.0%
CurrentChemical	0.1%	0.1%	0.0%	0.1%	0.0%	0.0%	0.0%
CurrentRooting	7.4%	11.5%	4.1%	7.4%	0.0%	0.0%	0.0%
CurrentTerrain	6.3%	9.7%	3.5%	6.3%	0.0%	0.0%	0.0%
Marginal total	48.6%	38.5%	-10.1%	27.0%	11.4%	10.2%	0.1%
Not Marginal	51.4%	61.5%	10.1%	51.3%			

[1] Total agricultural area based on CLC2018 (CLC level 1 agricultural areas) for EU27 + UK minus Cyprus and Malta.
[2] Surface areas per group of constraints is calculated as a summation. E.g. the current climate area is a summation of all areas where climate is a constraint without taking into account if any other constraint plays a role, thereafter the current wetness area is a summation of all areas where wetness is a constraint (and climate not) without taking into account if fertility, chemical, rooting and/or terrain constraints play a role.

The total area of environmental region Continental that is classified as marginal (focus on agricultural land) will increase in the period 2020-2050 by 0.8% (

Table 14). The increase applies to four of the six constraint clusters. Changes in the rooting and The total area of agricultural land that is mapped as marginal increased with 5,215km^2 from 127,333km^2 to 132,548km^2 in the Continental environmental zone.

From the total agricultural land 97.6% is not changing in marginality nor in one or a combination of constraints/marginal land type. Only for 0.8% of the total agricultural land the marginality land type will change towards 2050. For 0.4% (2,946km^2) of agricultural land that was only marginal in 2020 the climate or wetness constraints disappear. New marginal land in 2050 comprises 8,161km^2 or 1.2% of total agricultural land in the Continental region. Most of the new marginal land (7,898km^2) is mainly due to climate constraints alone, mostly increases in dryness. The changes in climate also lead to additional marginal land (263 km^2) in pairwise combinations with wetness and fertility (low SOC%).

Table 14. Land area share (km2 and %/agricultural area CLC 2018) of total and for 6 clusters of biophysical constraints making up marginal lands (mapped as severe and severe by pair-wise combination) for 2020 and 2050 for Environmental region Continental[1,2].

km2	2020	2050	difference	identical type 2020 - 2050	shift in type 2020 - 2050	only marginal in 2020	only marginal in 2050
CurrentClimate	4304	10976	6672	99	2400	1805	7898
CurrentWetness	41793	42228	435	40342	310	1141	63
CurrentFertility	8792	9037	245	8749	43	0	200
CurrentChemical	10865	9308	-1557	9308	1557	0	0
CurrentRooting	58562	57642	-920	57217	1345	0	0
CurrentTerrain	3017	3357	340	2995	22	0	0
Marginal total	127333	132548	5215	118710	5677	2946	8161
Not Marginal	552763	547548	-5215	544602			

%	2020	2050	difference	identical type 2020 - 2050	shift in type 2020 - 2050	only marginal in 2020	only marginal in 2050
CurrentClimate	0.6%	1.6%	1.0%	0.0%	0.4%	0.3%	1.2%
CurrentWetness	6.1%	6.2%	0.1%	5.9%	0.0%	0.2%	0.0%
CurrentFertility	1.3%	1.3%	0.0%	1.3%	0.0%	0.0%	0.0%
CurrentChemical	1.6%	1.4%	-0.2%	1.4%	0.2%	0.0%	0.0%
CurrentRooting	8.6%	8.5%	-0.1%	8.4%	0.2%	0.0%	0.0%
CurrentTerrain	0.4%	0.5%	0.0%	0.4%	0.0%	0.0%	0.0%
Marginal total	18.7%	19.5%	0.8%	17.5%	0.8%	0.4%	1.2%
Not Marginal	81.3%	80.5%	-0.8%	80.1%			

[1] Total agricultural area based on CLC2018 (CLC level 1 agricultural areas) for EU27 + UK minus Cyprus and Malta.

[2] Surface areas per group of constraints is calculated as a summation. E.g. the current climate area is a summation of all areas where climate is a constraint without taking into account if any other constraint plays a role, thereafter the current wetness area is a summation of all areas where wetness is a constraint (and climate not) without taking into account if fertility, chemical, rooting and/or terrain constraints play a role.

The total area of **environmental region Atlantic** classified as marginal land (focus on agricultural land) will decrease in the period 2020-2050 by 3.9% (

Table 15). The decrease is only for marginal land types where climate or wetness are a constraint. The total area of agricultural land that is mapped as marginal decreases with 23,381km^2 from 136,486km^2 to 113,105km^2. However, the area mapped as marginal due to the constraints grouped under fertility, chemical, rooting and terrain is not increasing in the Atlantic environmental zone.

From the total agricultural land 93.1% is not changing in marginality nor in one in a pairwise combination of constraints. For 2.9% of the total agricultural land the marginality land type changed. From the 3.9% of agricultural land that was only marginal in 2020 the climate or wetness constraints for 6,923km^2 respectively 16,716km^2 disappear. New marginal land in 2050 is almost absent and only appearing due to fact that an area of 258 km^2, which is less than 0.1% of total agricultural land, is meeting the wetness constraints by 2050.

Table 15. Land area share (km^2 and %/agricultural area CLC 2018) of total and for 6 clusters of biophysical constraints making up marginal lands (mapped as severe and severe by pair-wise combination) for 2020 and 2050 for Environmental Zone Atlantic[1,2].

km2	2020	2050	difference	identical type 2020 - 2050	shift in type 2020 - 2050	only marginal in 2020	only marginal in 2050
CurrentClimate	21181	256	-20925	250	14008	6923	0
CurrentWetness	83467	76761	-6706	63311	3440	16716	258
CurrentFertility	1511	2134	623	1508	3	0	0
CurrentChemical	3121	3123	2	3121	0	0	0
CurrentRooting	26125	29732	3607	26107	18	0	0
CurrentTerrain	1081	1099	18	1081	0	0	0
Marginal total	136486	113105	-23381	95378	17469	23639	258
Not Marginal	462464	485845	23381	462206			

%	2020	2050	difference	identical type 2020 - 2050	shift in type 2020 - 2050	only marginal in 2020	only marginal in 2050
CurrentClimate	3.5%	0.0%	-3.5%	0.0%	2.3%	1.2%	0.0%
CurrentWetness	13.9%	12.8%	-1.1%	10.6%			
CurrentFertility	0.3%	0.4%	0.1%	0.3%	0.0%	0.0%	0.0%
CurrentChemical	0.5%	0.5%	0.0%	0.5%	0.0%	0.0%	0.0%
CurrentRooting	4.4%	5.0%	0.6%	4.4%	0.0%	0.0%	0.0%
CurrentTerrain	0.2%	0.2%	0.0%	0.2%	0.0%	0.0%	0.0%
Marginal total	22.8%	18.9%	-3.9%	15.9%	2.9%	3.9%	0.0%
Not Marginal	77.2%	81.1%	3.9%	77.2%			

[1] Total agricultural area based on CLC2018 (CLC level 1 agricultural areas) for EU27 + UK minus Cyprus and Malta.
[2] Surface areas per group of constraints is calculated as a summation. E.g. the current climate area is a summation of all areas where climate is a constraint without taking into account if any other constraint plays a role, thereafter the current wetness area is a summation of all areas where wetness is a constraint (and climate not) without taking into account if fertility, chemical, rooting and/or terrain constraints play a role.

The total area of **environmental region Mediterranean** classified as marginal land (focus on agricultural land) is increasing in the period 2020-2050 by 6.6% (

Table 16). The total area of agricultural land that is mapped as marginal increased with 34,025km^2 from 157,503km^2 to 191,528km^2 towards 2050. From the total agricultural land 86.1% is not changing in marginality nor in a pairwise combination of constraints. For 6.6% of the total agricultural land the marginality land type will change. From 0.4% or 1,832km^2 of agricultural land that was only marginal in 2020 the wetness (and to limited extend climate) constraints disappear. New marginal land in 2050 amounts to 35,857km^2 or 6.9% of total agricultural land in the Mediterranean zone. The majority of the new marginal land in 2050 is due to climate (29,669km^2) alone and to climate in a pairwise combination with fertility (low SOC%, 6,009km^2), and also (to a lesser extent) with wetness (179 km^2).

Table 16. Land area share (km^2 and %/agricultural area CLC 2018) of total and for 6 clusters of biophysical constraints making up marginal lands (mapped as severe and severe by pair-wise combination) for 2020 and 2050 for Environmental Zone Mediterranean[1,2].

km^2	2020	2050	difference	identical type 2020 - 2050	shift in type 2020 - 2050	only marginal in 2020	only marginal in 2050
CurrentClimate	51255	114736	63481	51132	96	27	29669
CurrentWetness	6899	4487	-2412	4247	847	1805	179
CurrentFertility	46032	29775	-16257	23758	22274	0	6009
CurrentChemical	6614	5412	-1202	5405	1209	0	0
CurrentRooting	30554	21780	-8774	21371	9183	0	0
CurrentTerrain	16149	15338	-811	15311	838	0	0
Marginal total	157503	191528	34025	121224	34447	1832	35857
Not Marginal	361030	327005	-34025	325173			

%	2020	2050	difference	identical type 2020 - 2050	shift in type 2020 - 2050	only marginal in 2020	only marginal in 2050
CurrentClimate	9.9%	22.1%	12.2%	9.9%	0.0%	0.0%	5.7%
CurrentWetness	1.3%	0.9%	-0.5%	0.8%	0.2%	0.3%	0.0%
CurrentFertility	8.9%	5.7%	-3.1%	4.6%	4.3%	0.0%	1.2%
CurrentChemical	1.3%	1.0%	-0.2%	1.0%	0.2%	0.0%	0.0%
CurrentRooting	5.9%	4.2%	-1.7%	4.1%	1.8%	0.0%	0.0%
CurrentTerrain	3.1%	3.0%	-0.2%	3.0%	0.2%	0.0%	0.0%
Marginal total	30.4%	36.9%	6.6%	23.4%	6.6%	0.4%	6.9%
Not Marginal	69.6%	63.1%	-6.6%	62.7%			

[1] Total agricultural area based on CLC2018 (CLC level 1 agricultural areas) for EU27 + UK minus Cyprus and Malta.

[2] Surface areas per group of constraints is calculated as a summation. E.g. the current climate area is a summation of all areas where climate is a constraint without taking into account if any other constraint plays a role, thereafter the current wetness area is a summation of all areas where wetness is a constraint (and climate not) without taking into account if fertility, chemical, rooting and/or terrain constraints play a role.

Overall, in EU27+UK (minus Cyprus and Malta) the area of marginal land that occurs within the agricultural area is decreasing in the period 2020-2050. However, large differences exist within Europe. Looking at the different environmental zones the picture is diverse. The agricultural area occupied by marginal land is increasing in the Continental and especially in the Mediterranean environmental zone, while in the North, Alpine and Atlantic environmental zones the areas are decreasing. In all environmental zones the increase or decrease of climate constraints alone play the most prominent role while the area increasing because of pairwise combinations is limited.

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Annex I CHELSA data selection and pre-processing for Marginal land mapping in current and 2050 situation

As climate data source it was decided to use the CHELSA (Climatologies at high resolution for the earth's land surface areas). CHELSA (Karger et al. 2017; Karger et al. 2018) provides very high resolution (30 arc sec, ~1km) global downscaled climate data for the period 1981-2010, but also climate future scenarios for the periods 2011-2040, 2041-2070 and 2071-2100. As MIDAS is focussed on an updated marginal land map for 2020 and a future marginal land map for 2050, the periods 1981-2010 ('current') and 2041-2070 ('year 2050') have been selected.

CHELSA V2 is currently only available for a selected number of CMIP6 (Coupled Model Intercomparison Project Phase 6, the follow-up of CMIP5) scenarios, i.e. a selection of Global Climate Models (GCMs) and SSP (Shared Socioeconomic Pathways) combinations (more detailed information can be found here):

- The GCM selection follows the models given for the Intersectoral Impact Model Intercomparion Project (ISIMIP), which are:
  - GFDL-ESM4
  - UKESM1-0-LL
  - MPI-ESM1-2-HR
  - IPSL-CM6A-LR
  - MRI-ESM2-0
- The selected scenarios are SSP126, SSP370 and SSP585, which are updates of scenario SSP1, SSP3 and SSP5 with an additional radiative forcing of 2.6, 7.0 and 8.5 W/m2 respectively by the year 2100 (see Figure 8). SSP126 is a remake of the optimistic scenario RCP2.6. This scenario assumes climate protection measures being taken (CO_2 emissions cut to net zero around 2075). SSP585 represents the upper boundary of the range of scenarios described in the literature. It's an update of CMIP5 scenario RCP8.5, with very high fossil fuel emissions combined with socioeconomic reasons (CO_2 emissions triple by 2075). Within MIDAS it was decided to select the most extreme scenario SSP585.

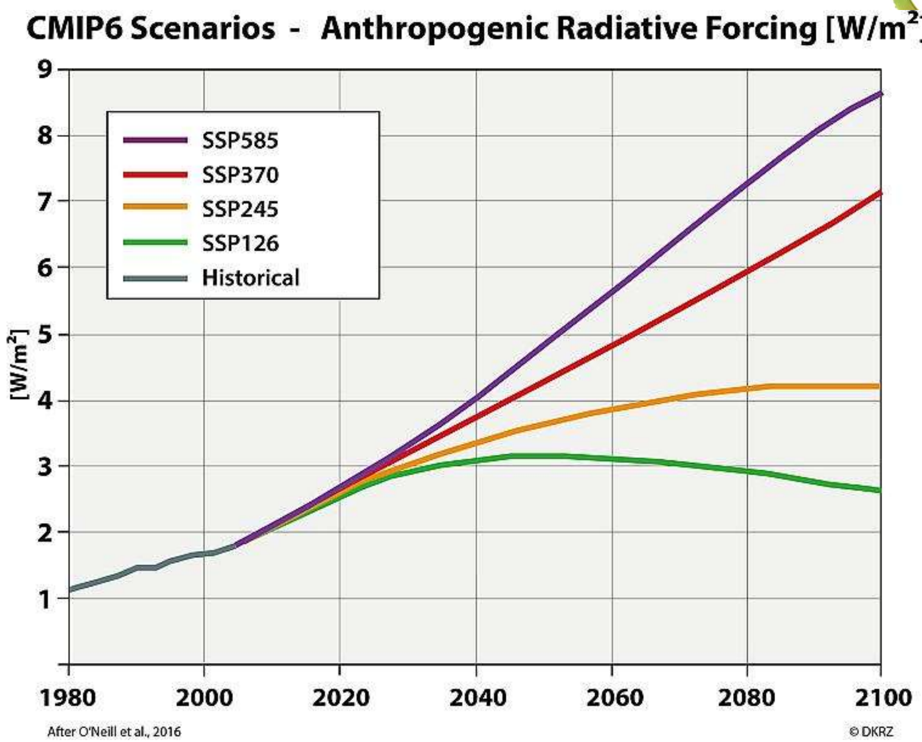

Figure 8: The temporal development of additional man-made radiative forcing resulting from the selected scenarios is depicted. The lines depict the development of the additional greenhouse-gas induced radiative forcing of the past (gray) and for the four SSP scenarios (green, yellow, red, purple).

The following climate data was downloaded the period 1981-2010, and future scenario period 2041-2070 for the 5 GCM models (listed above), i.e. 6 datasets:

- Daily mean/maximum/minimum air temperature at 2 metres from hourly ERA5 data for each month (TAS/TASMAX/TASMIN)
- Annual precipitation amount (BIO12)
- The heat sum of all days above the 5°C temperature accumulated over 1 year (GGD 5°C)

Derived climatic parameters:

- Annual potential evapotranspiration for reference grass (ETo or PET), based on the Hargreaves method. The annual sum was derived from monthly ETo's. Monthly ETo was derived from monthly air temperature data as follows:

  $ETo = 0.0023\ (T_{mean} + 17.8)\ (T_{max} - T_{min})^{0.5} * 0.408 * K_{rad}$, where K_{rad} is extraterrestrial radiation.

- The aridity index (AI) or degree of dryness, defined as the annual precipitation amount (BIO12) divided by the annual potential evapotranspiration (ETo).

  $AI = BIO12/ETo$

Note that the CHELSA data for 1981-2010 includes ETo and AI data. However, for the future scenario's these parameters are not provided. Instead these parameters have been derived ourselves for all 6 datasets.

- Monthly fraction of Soil Water Content (swc) available for evapotranspiration processes (as percentage of Maximum Soil Water Content). It's a measure of soil stress and equals to the soil water stress coefficient (Ksoil) as percentage. Here we followed the method of Trabucco et al. (2019) to derive monthly swc_fr (or excessive wetness) for the climatic data and 5x future scenarios. Finally, the monthly swc_fr results are converted into total number of days with saturated soil.

The model described by Trabucco et al. (2019) uses spatially distributed values of monthly precipitation and monthly potential evapotranspiration, and returns monthly spatially-distributed values defining actual evapotranspiration, runoff and soil water content (SWC). The modelling is spatially explicit to represent varying climate conditions, while vegetation and soil properties are assumed as uniformly standard (characterized by crop coefficient equal to 1, rain interception coefficient equal to 0.15 and maximum SWC in the rooting zone equal to 350 mm). Within MIDAS we have implemented the model of Trabucco et al. (2019) and rerun model but now based on the CHELSA data (current and future scenario). To achieve more realistic conditions of the initial SWC we repeated the simulation several years, before deriving the monthly swc_fr.

Downloaded data:

- Mean daily mean/max./min. air temp. + precip. amount per month; BIO12 (annual precip. amount), GGD 5°C (heat sum of all days above the 5°C temp. accumulated over 1 year)
- Derived parameters:
    - Aridity Index (AI) or degree of dryness, defined as annual precip devided by the annual reference evapotranspiration (PET). Monthly PET determined using Hargreaves method:
        - PET = $0.0023\ (T_{mean} + 17.8)\ (T_{max} - T_{min})^{0.5} * 0.408 * K_{rad}$
    - Monthly fraction of Soil Water Content (swc), following
        - Trabucco, Antonio; Zomer, Robert J. (2019): Global High-Resolution Soil-Water Balance https://doi.org/10.6084/m9.figshare.7707605.v3
        - Monthly swc_fr is converted to total no. Of days with saturated soil

Annex II Agricultural masks used for area share calculation

For the calculation of the relative area shares of the marginal land classes two agricultural masks were used in this report.

1) The MAGIC historic agricultural mask
2) MIDAS 2018 agricultural mask

Ad 1) The so-called MAGIC historic 'agricultural mask' includes all land that was classified in an agricultural land cover class (see Table II.1) in at least one of the four Corine Land Cover (CLC) versions:

CLC 1990

CLC 2000

CLC 2006

CLC 2012

Using this mask also enables to generate comparable statistics for an area of (former) agricultural land including potential abandoned agricultural lands.

Table II.1 CORINE land cover classes (CLC)* agricultural non agricultural

		MAGIC agricultural mask based on CLC 1990, 2000, 2012, 2018		MIDAS 2018 agricultural mask only based on CLC 2018	
CLC-NR	CLC Description_Level3	Grazing	Cropping	Grazing	Cropping
0	UNCLASSIFIED	No	No	No	No
111	Continuous urban fabric	No	No	No	No
112	Discontinuous urban fabric	No	No	No	No
121	Industrial or commercial units	No	No	No	No
122	Road and rail networks and associated land	No	No	No	No
123	Port areas	No	No	No	No
124	Airports	No	No	No	No
131	Mineral extraction sites	No	No	No	No
132	Dump sites	No	No	No	No
133	Construction sites	No	No	No	No
141	Green urban areas	No	No	No	No
142	Sport and leisure facilities	No	No	No	No
211	Non irrigated arable land	No	**Yes**	No	**Yes**
212	Permanently irrigated land	No	**Yes**	No	**Yes**
213	Rice fields	No	**Yes**	No	**Yes**
221	Vineyards	No	**Yes**	No	**Yes**
222	Fruit trees and berry plantations	No	**Yes**	No	**Yes**
223	Olive groves	No	**Yes**	No	**Yes**

		MAGIC agricultural mask based on CLC 1990, 2000, 2012, 2018		MIDAS 2018 agricultural mask only based on CLC 2018	
CLC-NR	**CLC Description_Level3**	**Grazing**	**Cropping**	**Grazing**	**Cropping**
231	Pastures	**Yes**	No	**Yes**	No
241	Annual crops associated with permanent crops	No	**Yes**	No	**Yes**
242	Complex cultivation patterns	**Yes**	**Yes**	**Yes**	**Yes**
243	Land principally occupied by agriculture- with significant areas of natural vegetation	**Yes**	**Yes**	**Yes**	**Yes**
244	Agro forestry areas	**Yes**	**Yes**	**Yes**	**Yes**
311	Broad-leaved forest	No	No	No	No
312	Coniferous forest	No	No	No	No
313	Mixed forest	No	No	No	No
321	Natural grasslands	**Yes**	No	**Yes**	No
322	Moors and heathland	**Yes**	No	**No**	No
323	Sclerophyllous vegetation	No	No	No	No
324	Transitional woodland shrub	No	No	No	No
331	Beaches- dunes- sands	No	No	No	No
332	Bare rocks	No	No	No	No
333	Sparsely vegetated areas	No	No	No	No
334	Burnt areas	**Yes**	**Yes**	**No**	**No**
335	Glaciers and perpetual snow	No	No	No	No
411	Inland marshes	No	No	No	No
412	Peat bogs	No	No	No	No
421	Salt marshes	No	No	No	No
422	Salines	**Yes**	No	**Yes**	No
423	Intertidal flats	No	No	No	No
511	Water courses	No	No	No	No
512	Water bodies	No	No	No	No
521	Coastal lagoons	No	No	No	No
522	Estuaries	No	No	No	No
523	Sea and ocean	No	No	No	No

*For a detailed description of all CORINE 2012 classes see: http://uls.eionet.europa.eu/CLC2000/classes/index_html

Ad 2) The MIDAS agricultural mask is purely based on the CLC 2018 and only includes agricultural land cover classes (see Table II.1). It is more suitable to apply to be used for comparing the marginal land area changes between 2020 and 2050.

The project has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement No. 101082070.

The consortium