Deliverable 4.1: Low-input agricultural practices for industrial crops on marginal land

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1.Introduction

1.1. Context and objective

Bioeconomy is “the knowledge-based production and utilization of biological resources to provide products, processes and services in all sectors of trade and industry within the framework of a sustainable economic system” (German Bioeconomy Council, 2015). A growing bioeconomy involves the replacement of fossil by biogenic resources (or biomass) derived from plants, animals or microorganisms. According to the National Renewable Energy Action Plans of the European member states, about double the amount of biomass used for energetic purposes in the year 2012 will be required by 2020. In addition, it is expected that more than 80 million tons of bioproducts will be produced in 2020 (Scarlat et al., 2015) and potentially about 150 million tons of fossil-based products and chemicals could be replaced by biobased products. This indicates a substantial demand for additional biomass to fulfill the EU’s bioeconomy goals.

In the envisioned "ideal" bioeconomy, biomass production will take ecological, social and health aspects into consideration (Staffas et al., 2013). From the definitions and ambitions of the bioeconomy, it can be concluded that its growth will require a sufficient supply of sustainably produced biomass. According to (Scarlat et al., 2015), the potential risks arising from increased biomass production and supply in Europe are:

- The move towards a bioeconomy based on natural resources from land and sea would lead to a large increase in the demand for biomass undermining the sustainability of a biobased economy.
- Additional land use could lead to negative impacts from land-use change, such as biodiversity, soil carbon and soil fertility losses.
- The need to increase crop productivity could lead to increased use of fertilizers and pesticides with additional problems related to water and soil pollution.
- Additional pressure on water resources.
- Increasing competition for resources between food supply and non-food biomass.

The MAGIC project has been established with the ambition of helping mitigate these risks. The results of the MAGIC project will contribute to the development strategy for sustainable biomass supply in a growing European bioeconomy by applying the following strategies:

A) Identification and mapping of marginal land (Development of MAEZ); with marginal land being defined as land that has bio-physical and/or socio-economic constraints for food production. The definition of "marginal land" given in Box 4.1.1 is the one elaborated in

Box 4.1.1 Definition of marginal land in the context of MAGIC (Elbersen et al., 2018b)

"lands having limitations which in aggregate are severe for sustained application of a given use and/or are sensitive to land degradation, as a result of inappropriate human intervention, and/or have lost already part or all of their productive capacity as a result of inappropriate human intervention and also include contaminated and potentially contaminated sites that form a potential risk to humans, water, ecosystems, or other receptors."

In the classification of marginal lands, the MAGIC project additionally specifies that indirect land-use effects and competition with food production are to be avoided. This means that marginal lands need to be further divided into used marginal land, unused marginal land and lands where the biophysical limitations no longer apply because improvements measures have facilitated productive agriculture.

MAGIC deliverable 2.1. (Elbersen et al., 2018b) as a basis for identifying marginal land in Europe. This approach allows the identification of agricultural land unsuitable for food production, thereby avoiding a competition for land resources between food supply and non-food biomass production for a growing bioeconomy.

B) Careful selection of suitable industrial crops; this will be carried out based on prevailing biophysical conditions of the marginal lands and considering potential impacts on ecosystems services. Thus, the selection of crops within MAGIC aims not only at achieving high yields but also helps to create co-benefits such as improving soil health and restoring long-term productivity, particularly in the case of degraded lands. The selection of industrial crops in MAGIC takes into consideration their yield potential and quality suitability for biomass use. At the same time crops are selected that can deal with marginality constraints, such as drought, contamination and slopes. Such crops are often characterized by high water and nutrient use efficiency. This reduces the pressure on water resources and demand for fertilizers.

About half of the crops selected for detailed research and field trials in MAGIC are perennial biomass crops, e.g. perennial grasses, trees and thistles (Tables 1, A1). Perennial biomass crops (PBC) have the following advantages (Lewandowski, 2016).

Table 1: Overview of physiological and technical characteristics of the crops selected for detailed research and field trials.

Crop		Physiology		Purpose / Type of use
Common name	Binomial name	Life cycle	Photosynthetic pathway	
Biomass sorghum	*Sorghum* Moench 1794	Annual	C4	Multipurpose
Camelina	*Camelina sativa* L. Crantz	Annual	C3	Oil
Cardoon	*Cynara cardunculus* L.	Perennial	C3	Multipurpose
Castor bean	*Ricinus communis* L.	Annual	C3	Oil
Crambe	*Crambe* L.	Annual	C3	Oil
Ethiopian mustard	*Brassica carinata* A.Braun	Annual	C3	Oil
Giant reed	*Arundo donax* L.	Perennial	C3	Lignocellulosic
Hemp	*Cannabis sativa* L.	Annual	C3	Multipurpose
Lupin	*Lupinus* L.	Perennial	C3	Multipurpose
Miscanthus	*Miscanthus* ANDERSSON	Perennial	C4	Lignocellulosic
Pennycress	*Thlaspi* L.	Annual	C3	Oil
Poplar	*Populus* L.	Perennial	C3	Wood
RCG	*Phalaris arundinacea* L.	Perennial	C3	Lignocellulosic
Safflower	*Carthamus tinctorius* L.	Annual	C3	Oil
Siberian elm	*Ulmus* L.	Perennial	C3	Wood
Switchgrass	*Panicum virgatum* L.	Perennial	C4	Lignocellulosic
Tall wheatgrass	*Thinopyrum ponticum* Podp. Z.-W.Liu & R.-C.Wang	Perennial	C4	Lignocellulosic
Wild sugarcane	*Saccharum spontaneum* L.	Perennial	C4	Lignocellulosic
Willow	*Salix alba* L.	Perennial	C3	Wood

PBC have low input requirements and their cultivation is associated with very low GHG emissions: Due to their perennial growth and ability to recycle and store nutrients over winter in underground roots and rhizomes, PBC have comparatively low fertilization requirements. Recycling is especially efficient for N, which is associated with the highest proportion of GHG emissions in crop production. Under some circumstances, the productive cultivation of PBC without application of N fertilizers is possible. In addition, apart from herbicides during the first establishment years, most PBC require little, if any, pesticide application for healthy growth. Tillage is required in the year of establishment only. Together, these factors allow for biomass production with low inputs and low GHG emissions.

PBC cultivation does not require annual ploughing, thus leading to improved soil fertility, carbon sequestration and biodiversity: The productive period of PBC ranges from 10 to 25 years, depending on the crop. Long-term soil rest is ensured as no intensive soil cultivation - required for crop establishment - is performed after the year of planting. Together with the increased return of organic matter, this leads to sequestration of soil carbon, improvement in soil fertility and increase in soil biodiversity. Many PBC, such as rhizomatous grasses,

are harvested in early spring and others, mainly short rotation coppice, are only harvested once every 3-4 years. Therefore, PBC fields provide shelter for birds and mammals over winter and harvesting is not performed during the breeding season.

PBC are stress-tolerant and can be produced under marginal conditions: Once established, PBC are more stress-tolerant than annual crops because they root deeply and, from the second year on, are not dependent on optimal establishment conditions, such as sufficient precipitation or soil workability. This deep rooting and long-term soil rest mean that established plantations provide protection against erosion, for example on slopes (Cosentino et al., 2015). Droughts can be overcome more easily once deep roots have developed. Tolerance of many types of stress have been reported, including droughts, salinity, cold and contaminations, e.g. in various miscanthus genotypes (Lewandowski et al., 2016), giant reed clones (Cosentino et al., 2014; Sánchez et al., 2015) and perennial wild plant species (von Cossel and Lewandowski, 2016).

However, annual crops also need to be chosen for field testing in MAGIC because some products urgently required for a growing bioeconomy are mainly produced by annual crops (Zanetti et al., 2013). This is especially relevant for the production of vegetable oils, but most sugar- and starch-producing crops are also annuals. Many of the annual crops chosen are multi-purpose as their products can be used for different applications in the material, energetic or pharmaceutical sectors. Perennial biomass crops mainly produce lignocellulosic biomass, whereas some annual crops such as hemp and cardoon can produce fibres as well as vegetable oil and pharmaceutics.

C) Development of site-specific cultivation systems for selected crops aims to ensure both optimal agronomic output (biomass yield and quality) and potential benefits for ecosystem services. On marginal lands however, the establishment and long-term economic viability of the cropping systems is expected to be challenging, because crop establishment effort is often higher and yields are generally lower than under good agricultural production conditions (van Dam et al., 2009). Therefore, it is extremely important to introduce a system with closed nutrient cycles in order to promote on-farm nutrient recycling and reduce the dependency on off-farm resources such as agrochemicals and energy. For this reason, low-input practices that minimize the demand for off-farm resources and optimize resource-use efficiency - often part of modern, low-input agricultural farming systems e.g. precision farming, organic farming etc. - are becoming ever more relevant for the management of marginal lands.

1.2. Definition of low-input agricultural practices

The objective of MAGIC is to assess the potential for sustainably produced biomass from marginal lands. One pillar of the sustainability approach is the application of “low-input agricultural practices”. The following sections describe the conceptual understanding of low-input agricultural practices on which our recommendations for industrial crop management on marginal lands are based.

Various definitions of low-input agricultural systems can be found in the literature.

The definition of low-input systems by Altieri (2002) exclusively emphasizes the need for internal inputs to be increased to allow for optimal productivity*: “A variety of projects exist featuring resource-conserving yet highly productive systems such as polycultures, agroforestry, the integration of crops and livestock, etc. (Altieri et al., 1998). Such alternative approaches can be described as low-input technologies, but this designation refers to the external inputs required. The amount of labor, skills and management that are required as inputs to make land and other factors of production most productive is quite substantial. So rather than focus on what is not being utilized, it is better to focus on what is most important to increase food output, labor, knowledge and management (Uphoff and Altieri, 1999)”.*

A definition of low-input farming systems that extends its coverage beyond internal input use to the reduction of environmental impacts is provided by Parr *et al*. (1990): low-input farming systems are those that "*seek to optimize the management and use of internal production inputs (i.e. on-farm resources)... and to minimize the use of production inputs (i.e. off-farm resources), such as purchased fertilizers and pesticides, wherever and whenever feasible and practicable, to lower production costs, to avoid pollution of surface and groundwater, to reduce pesticide residues in food, to reduce a farmer's overall risk, and to increase both short- and long-term farm profitability.*"

This definition reflects one of the major motivations for striving towards low-input agricultural systems: environmental concerns. Agricultural intensification since the 1950ies, accompanied by an increasing use of agrochemicals and mechanization, has been made responsible for major environmental problems. According to Baldock *et al*. (2002), the pollution of water resources, loss of biodiversity and increase in erosion problems can be broadly associated with the withdrawal of landscape ecology features and increased use of agricultural inputs, especially pesticides and mineral fertilizers. Therefore, a minimization in or at least reduction of external inputs is expected to reduce both environmental pressure and also anticipated negative effects of agrochemicals on human health (Biala et al., 2007) (see Figure 1). The idea of ‘optimizing’ and ‘minimizing’ inputs is nevertheless rather general. Norman et al. (1997) note that the term is "*somewhat misleading and indeed*

unfortunate. For some it implied that farmers should starve their crops, let the weeds choke them out, and let insects clean up what was left. In fact, the term low-input referred to purchasing few off-farm inputs (usually fertilizers and pesticides), while increasing on-farm inputs (i.e. manures, cover crops, and especially management). Thus, a more accurate term would be different input or low external input rather than low-input."

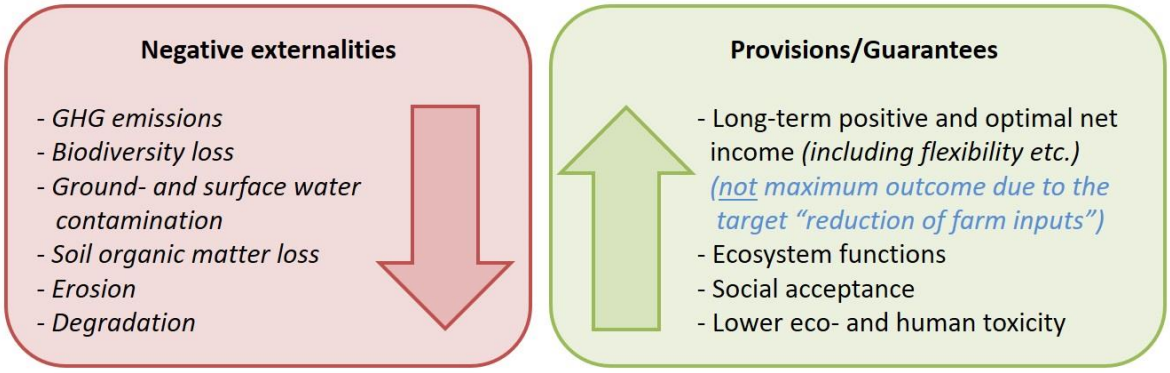

Figure 1: Potential negative externalities of conventional systems and provisions/guarantees expected as an outcome of low-input agricultural systems.

Low-input systems are most often defined at farm-level. Biala et al. (2007) define 'Low-input farming systems (LIFS)' "as those which maximize the use of on-farm inputs. Compared to farming systems heavily relying on off-farm bought inputs (thus high input farming systems or HIFS), LIFS will have a physical productivity limited by the maximum on-farm resources that can be mobilized. LIFS can then be associated with lower output." But at the same time, Biala et al. (2007) also associate LIFS with lower yields or outputs. The approach most often applied to practically describe LIFS is to divide them into the farming systems 'low-input farms' (e.g. those with extensive grazing), 'organic farms' and 'high nature value (HNV) farms' (Biala et al., 2007). The concept of HNV farms was first introduced by Baldock et al. (1993): "*High Nature Value (HNV) farming systems are predominantly low-intensity systems which often involve a relatively complex interrelationship with the natural environment. They maintain important habitats both on the cultivated or grazed area (for example, cereals steppes and semi-natural grasslands) and in features such as hedgerows, ponds and trees, which historically were integrated with the farming systems. […] The semi-natural habitats currently maintained by HNV farming are particularly important for nature conservation in the EC because of the almost total disappearance of large scale natural habitats*".

This definition of HNV farming systems is rather conceptual. More practical (in terms of providing clear management guidelines) definitions of LIFS can be found for integrated, organic, precision and conservation farming (see Box 4.1.2) (Lewandowski et al., 2018).

Box 4.1.2 Farming concepts with a clear definition (rather than a conceptual approach) (1.-3. taken from Lewandowski et al., 2018)

1. Integrated farming

Integrated farming seeks to optimize the management and inputs of agricultural production in a responsible way. This approach aims at minimizing the input of agrochemicals and medicines to an economical optimum and include ecologically sound management practices as much as possible. As an example, "Integrated Pest Management (IPM)" refers to the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human and animal health and/or the environment. Moreover, the close linkage of crop and livestock components in agro-ecosystems allows for efficient recycling of agricultural by-products or wastes, thereby reducing the reliance on external inputs such as fertilizers and animal feeds.

2. Organic farming

"Organic Agriculture is a production system that sustains the health of ***soils, ecosystems*** *and* ***people****. It* ***relies on ecological processes, biodiversity and cycles adapted to local conditions****, rather than the use of inputs with adverse effects. Organic Agriculture combines* ***tradition, innovation*** *and* ***science*** *to benefit the shared environment and promote* ***fair relationships*** *and a good* ***quality of life*** *for all involved."* (IFOAM 2005). There are several variants of organic agriculture, including organic livestock production. All of them forbid the use of synthetic pesticides and fertilizers in crop production. Crop nutrient demands and crop health are managed through biological methods of N fixation, crop rotation and the application of organic fertilizer, in particular animal manure.

3. Precision farming

Precision farming is a management approach based on the spatially specific and targeted management of agricultural land and fields. It makes use of modern agricultural production technology and is often computer-aided. In crop farming, the objective of precision farming is to take account of small-scale differences in management demand within fields. Sensors that assess the nutritional status and health of crops support their spatially differentiated management.

4. Conservation Farming

"*Conservation Agriculture (CA) is an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment. CA is characterized by three linked principles, namely:*

- Continuous minimum mechanical soil disturbance.

- Permanent organic soil cover.

- Diversification of crop species grown in sequences and/or associations." (FAO 2018)

However, the definition of low-input practices at a systems level appears inflexible, in the sense that these practices are technological approaches, which - especially in the case of organic farming - are overlaid by strict and exclusive management rules. Especially when confronted with challenges such as marginal production conditions, it seems more appropriate to combine the most suitable management practices as intelligently as possible. Biala et al. (2007) rightly concludes that the most appropriate low-input strategy depends not only on site conditions but also on farming conditions, i.e. access to modern/efficient varieties and mechanization and production goals. Therefore, we have chosen a definition of low-input agricultural practices that provides sufficient flexibility to address the demands of successful crop management on marginal lands (see Box 4.1.3).

Box 4.1.3 Definition of low input agricultural practices

"In the MAGIC project, low-input practices are defined as a part of agricultural management systems for sustainable crop production, which focuses on achieving high output through selection of appropriate crop type or development of new varieties taking into consideration the prevailing marginality constraints and adopting such agronomic practices that not only fulfil optimal crop requirements but also enhance environmental and ecological services and contribute towards developing farm economy for a specific climatic zone."

Our definition of low-input agricultural practices is in line with approaches formulated as "ecological intensification", "agro-ecological intensification" or "sustainable intensification". These are defined according to Wezel et al. (2015) as follows:

- Sustainable intensification: Producing more from the same area of land while conserving resources, reducing negative environmental impacts and enhancing natural capital and the flow of environmental services.
- Ecological intensification: Increasing food production while reducing the use of external inputs and minimizing negative effects on the environment by capitalizing on ecological processes and ecosystem services from plot to landscape scale.
- Agroecological intensification: Improving the performance of agriculture while minimizing environmental impacts and reducing dependency on external inputs through integration of ecological principles into farm and system management.

These three concepts, of which sustainable intensification is the most commonly used, overlap to a large extent. But they are all characterized by the two common key elements of "increased production" and "minimized environmental impacts". They mainly differ in their focus with 'sustainable intensification' being more general, 'ecological intensification' emphasizing the understanding and intensification of biological and ecological processes

and functions in agroecosystems, and 'agroecological intensification' accentuating the system approach and integrating more cultural and social perspectives (Wezel *et al*., 2015).

With respect to sustainable intensification, we rely on the definition of low-input agriculture

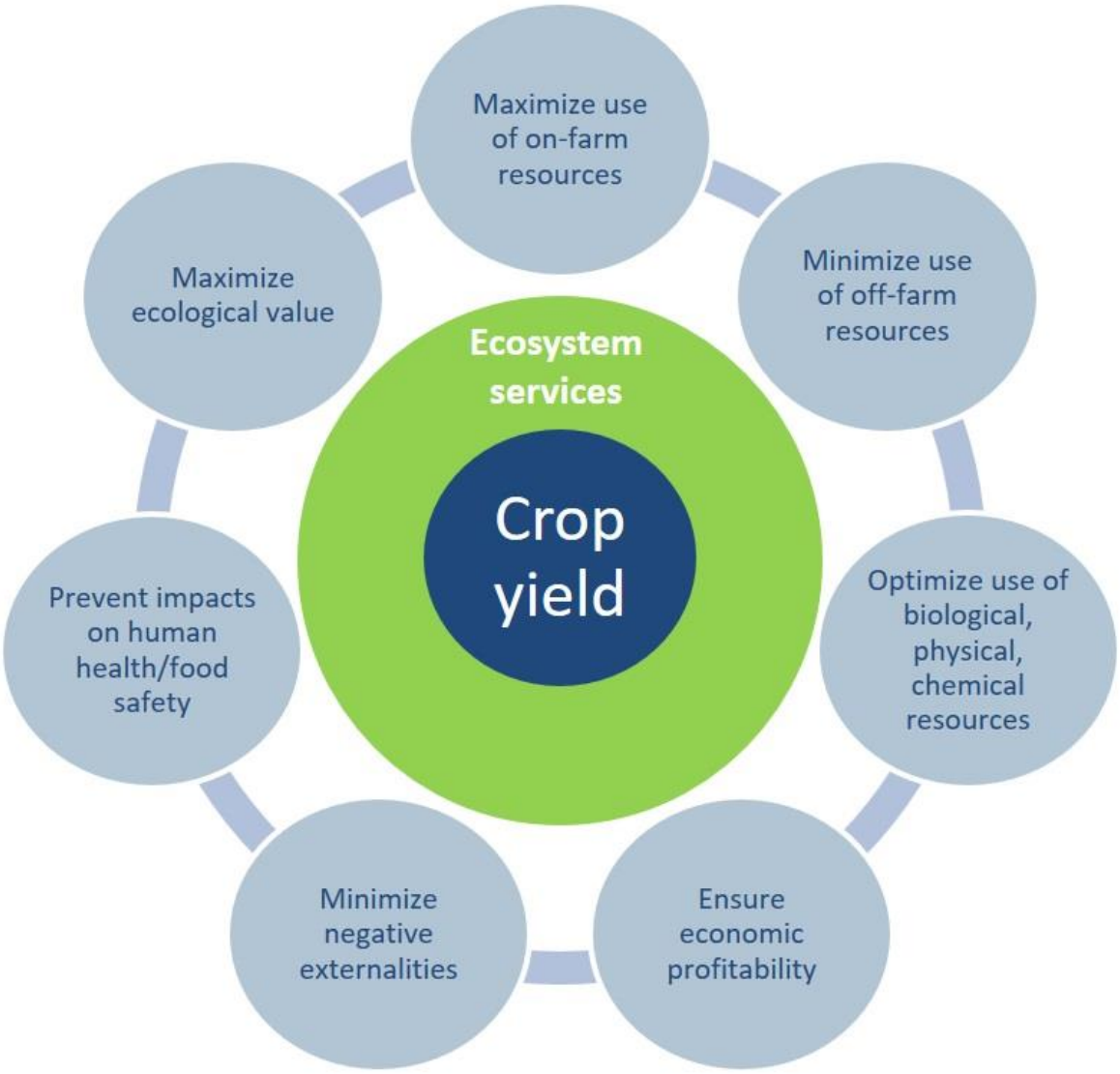

Figure 2: Principles of low-input agriculture.

as a system which uses low inputs to deliver high output per unit of land along with positive impacts on ecosystem services and which helps to counter socio-economic and environmental challenges (Baulcombe et al., 2009; Godfray et al., 2010; Pretty, 2008; Pretty et al., 2011; Pretty and Bharucha, 2014). Low-input agriculture aims to improve efficiency through adopting appropriate low-input practices and reducing emissions produced per unit of product, subsequently reducing input requirement per hectare (Pointereau et al., 2012). Therefore, the focus of low-input agriculture is not only on minimizing or devising low input practices but is rather an evaluation of the whole system in terms of efficiency and productivity (Biala et al., 2007). Figure 2 depicts the elements and objectives of low-input agriculture.

Low-input agricultural practices seek to optimize on-farm resources and minimize off-farm resources. This translates into a more ‘closed’ production cycle (and consequently less external inputs) and requires more advanced agronomic skills. Agronomic strategies for the successful application of low-input agricultural practices should be seen as a set of strategies that take account of the interactions between soil, plants, atmosphere and optimal use of input in order to achieve the highest output with minimal (on-farm and/or off-farm) input supply. Agronomic strategies for low-input agriculture may also match good agricultural practices - cultivation practices that address the environmental, economic and social sustainability of on-farm processes (FAO, 2018) and result in safe, quality food and non-food agricultural products. Such practices include soil management. This aims to maintain or improve soil organic matter through the build-up of soil carbon by appropriate crop rotations, manure application, pasture management and other land-use practices, rational mechanical and/or conservation tillage practices. Long crop rotation is one way to control pests and weeds, reduce reliance on synthetic chemicals, prevent soil-borne diseases, maintain soil fertility and reduce soil erosion, leading to off-farm input reductions. Reduced soil tillage, as practiced in conservation agriculture, is a method of increasing soil fertility, reducing soil erosion, increasing organic matter and improving water-buffer capacity. Water management is a major challenge in agriculture and requires the adoption of techniques to monitor crop and soil water status, accurately schedule irrigation, etc. Fertilizers and agrochemicals should be applied in a balanced fashion, with appropriate methods and equipment and at adequate intervals to replace nutrients extracted by harvest or lost during production. Crop protection should be conducted in a way that maximizes biological prevention of pests and diseases, in particular promoting integrated pest management (IPM). This includes the applications of agrochemicals according to threshold levels, the selection of resistant cultivars and varieties, practice crop sequences, and proper cultural practices. The possibility of cultivating the industrial crops selected here on contaminated land will reduce the threats to human health and the environment, while at the same time offering the opportunity of economic revenue to rural populations.

For the practical development of low-input production systems, we neither intend to select one of the farming concepts described in Box 4.1.2, nor rely on one of the intensification concepts. Instead, our approach is the choice and combination of the best farming practices for a specific marginal site with the objective of achieving high productivity and at the same time minimizing environmental impacts. For this purpose, we analyze the farming practices underlying the different farming concepts.

The optimal low-input agricultural practices to be applied on marginal lands vary from region to region based on marginality constraints, prevailing climatic conditions, local demands, and ecological and environmental challenges specific to that region (Schulte et al., 2014). In MAGIC, the main focus is on the development of low-input practices for marginal lands prevailing in Continental, Atlantic and Mediterranean climatic zones.

To date, agricultural practices are mainly designed for food crop production on good agricultural soil. The ambition of the MAGIC project is to extend the application of the low-input agricultural practices mentioned above to selected industrial crops grown on several types of marginal land, including contaminated land. All agronomic practices for establishment and cultivation will be adjusted to conform to low-input agriculture.

Thus, the overall objective of this study is to define low-input agricultural practices and develop low-input agricultural management systems for selected industrial crops for the most prevalent European marginal lands.

1.3. Approach and structure of this deliverable

In Chapter 1, the concept of low-input sustainable agricutural practices was defined as the basis for the development of concrete low-input agricultural management systems for selected industrial crops for most prevalent European marginal lands.

Chapter 2 introduces the biophysical marginality constraints relevant for Europe. A literature review and expert survey on management measures suitable for dealing with these biophysical constraints is performed. These include management measures on a structural level (e.g. shaping landscape structures), a cropping-system level and on a crop-management level. Finally, the choice of suitable crops is addressed and the selected industrial crops are analyzed for their potential to contribute to overcoming biophysical marginality constraints.

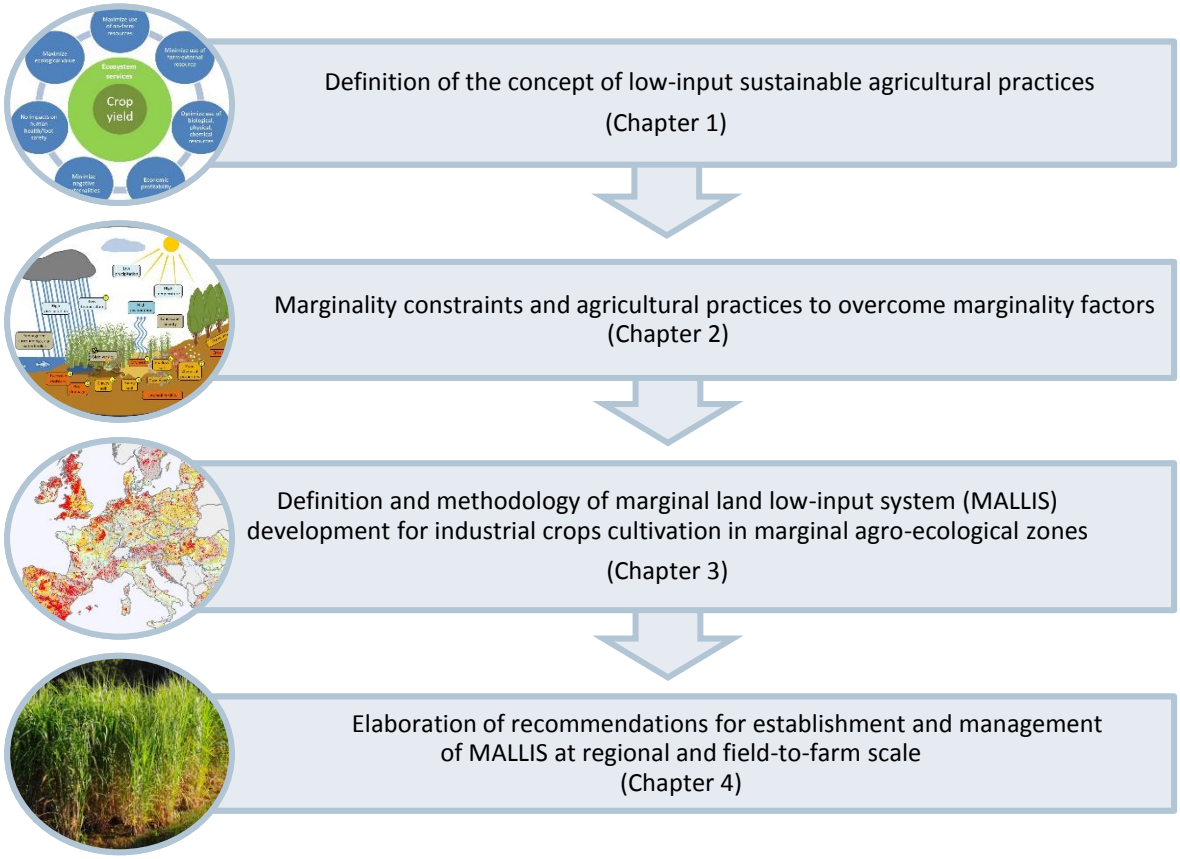

Figure 3: Approach and structure of this deliverable.

In Chapter 3, the definition and methodology of marginal land low-input system (MALLIS) development for selected "industrial crop – MAEZ (Marginal Agro-Ecological Zones) scenarios are described. MALLIS is defined here as a set of low-input practices which form relevant management components of viable cropping systems on marginal lands under specific climatic conditions and are sustainable in both socio-economic and environmental terms. A MAEZ is the combination of biophysical limitation(s) and climatic zone. The identification procedure of the most prevalent MAEZ for Europe is described in this chapter.

Finally, in Chapter 4, recommendations for the establishment and management of field trials to be conducted in MAGIC are elaborated. For this purpose, MALLIS are developed on both regional (MAEZ) and field-to-farm scale, e.g. the new field trials to be established within MAGIC.

2. Marginality constraints and agricultural practices to overcome them

The cultivation of industrial crops on lands defined as marginal for food crop cultivation faces both biophysical constraints as well as socio-economic challenges (Fig. 4). However, there is only scarce information available on both the mechanisms and distributions of industrial crop-specific marginality constraints in Europe. This information is required

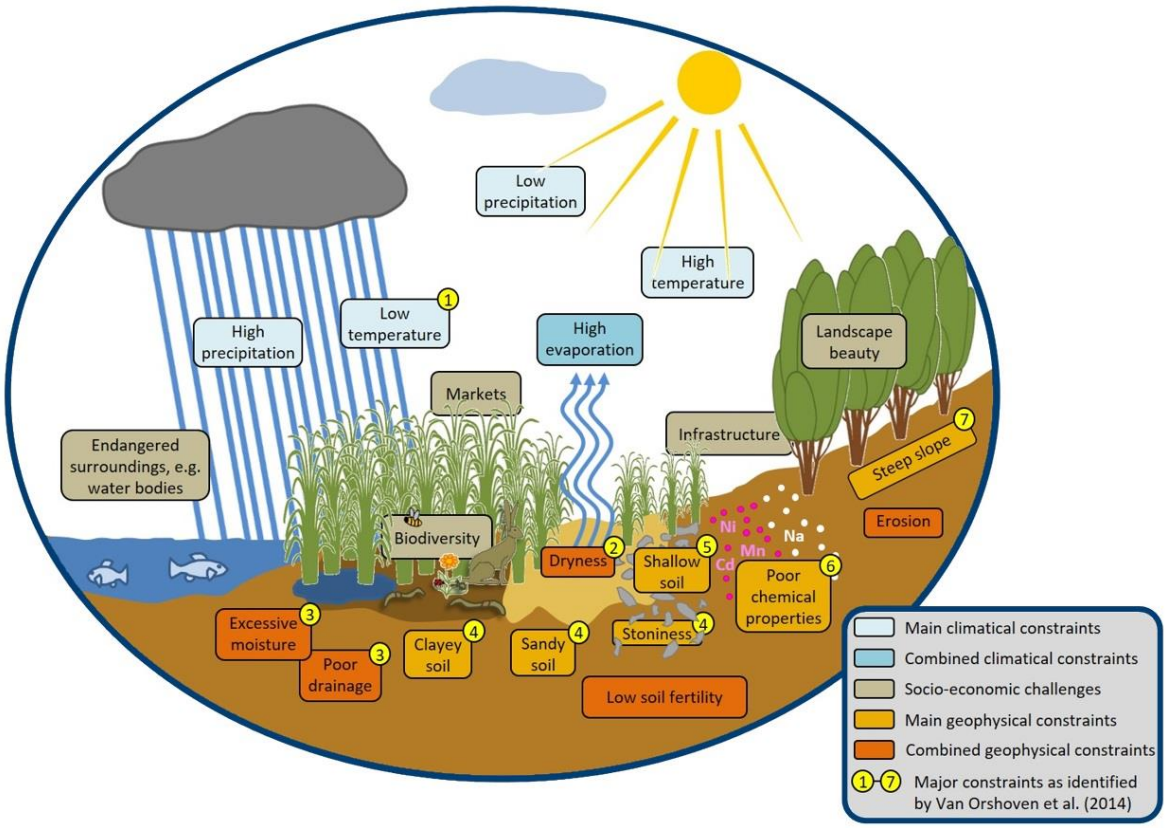

Figure 4: Illustration of relevant biophysical constraints and socio-economic challenges selected for MALLIS development within MAGIC. Numbers 1-7 indicate the major biophysical constraints for food crop production as defined by Van Orshoven et al. (2012, 2014). The other parameters have been added based on expert opinion; they either influence (main constraints) or follow on from (combined constraints) those defined by Van Orshoven et al. (2012, 2014). The same applies to the socio-economic challenges which have been added due to their increasing relevance for modern arable systems (Hallmann et al., 2017; Isbell et al., 2017; Nichols and Altieri, 2013; Potts et al., 2016; Tilman et al., 2009).

because a careful selection of industrial crops optimized to suit site-specific conditions is the first and most important agricultural practice for successful implementation of MALLIS across Europe's MAEZ identified within MAGIC. Chapter 2 aims to close these crucial knowledge gaps by reviewing how the pre-selected industrial crops (Table 1) could adapt the given site-specific climate conditions of the agro-ecological zones (AEZ) (Fig. 5) and the prevailing constraints (MAEZ). For example, a low level of precipitation of about 300 mm a^{-1} renders a site marginal for a high water-demanding industrial crop such as reed canary

grass or willow, whereas the same level could be sufficient for successful cultivation of industrial crops with low water demands such as camelina or crambe (Table 8).

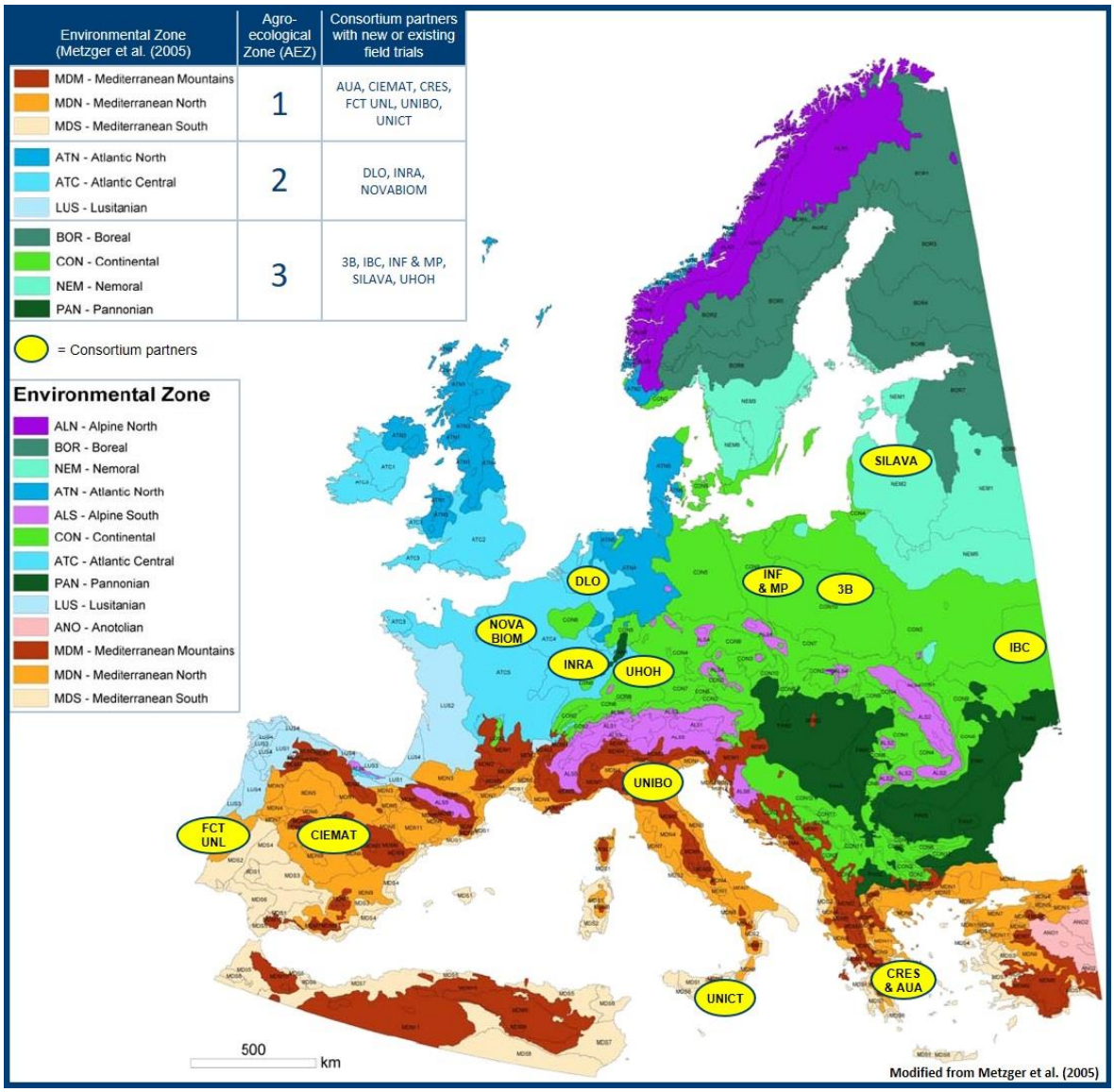

Figure 5: Distribution of agro-ecological zones taken into consideration for the development of marginal land low-input systems for industrial crops across Europe modified from Elbersen et al. (2018a) and Metzger et al. (2005).

The prevailing biophysical marginality constraints for food crop cultivation (Fig. 4, Table 2) were chosen based on the outcome of several reports prepared by the Joint Research Centre of the European Commission (Terres et al., 2014; Van Orshoven et al., 2014, 2012). Van Orshoven et al. (2014, 2012) also provide detailed information, including threshold levels, on 7 major marginality constraints and 14 sub-categories (see category 1, Table 2). These were used to define the MAEZ, i.e. those areas of land defined as unsuitable for food

crop production and therefore available for industrial crop cultivation without impeding food security.

Table 2: Overview of the three categories of marginality constraints as classified within this deliverable. Category 1 was adapted from Van Orshoven et al. 2014. Categories 2 and 3 were developed based on literature review and expert opinion.

Constraint category	Factor category	Thresholds/specifications
Category 1: "Natural constraint based marginality"	Low temperature (insufficient thermal time)	Length of growing period ≤ 180 days
		Thermal time sum ≤ 1500 degree days
	Dryness – Too dry conditions	Precipitation / Potential Evapotranspiration (P/ET ≤0.5)
	Limited soil drainage and excess soil moisture	Wet 80 cm > 6 months
		Wet 40 cm > 11 months
		Poorly or very poorly drained
		Gleyic colour pattern within 40 cm
		Soil moisture above field capacity for >230 days (excessive soil moisture)
	Unfavourable soil texture and stoniness	Topsoil with stones (15% of topsoil volume is coarse material, rock outcrop, boulder)
		Texture class in half of the soil in a profile of 100 cm vertical depth is sand, loamy sand
		Organic soil, defined as having 'organic matter ≥ 30% of at least 40 cm
		Topsoil with 30% or more clay and presence of vertical properties within 100 cm
	Shallow rooting depth	The physical anchorage of the rooting system (rooting depth ≤ 30 cm)
		The provision/storage of nutrients and water
		The possibility of mechanized tillage
	Poor chemical properties (Soil salinity, soil sodicity, soil acidity)	The possibility of mechanized tillage
		Limitation to plant growth due to toxic elements in soil
		Vulnerability to waterlogging
		Damage to soil structure (and consequently increase in risk of erosion)
		Limited availability of nutrients for plants
		Salinity ≥ 4 dS/m in topsoil
		Sodicity ≥ 6 ESP in half or more of the 100-cm surface layer
		Soil Acidity of topsoil with pH (H20) ≤ 5
	Steep slope	Slope ≥ 15%
Category 2: "Socio-economic-political constraints"		Lack of awareness (alternative strategies – lack of know-how etc.)
		Social norms (adoption of same cropping patterns as done by elders)
		Economic viability, especially of set-aside, small land holdings
		Lack of infrastructure
		Lack of policies
		Lack of governmental programs such as extension services
Category 3: "Endangered Sites"		Lands which are currently productive but will be transformed into marginal lands in the long term if not managed properly (also, lack of know-how or lack of awareness from farmers/government).

Another JRC report investigated the interactions between individual marginality constraints (Table 3) and revealed strong synergistic effects for some combinations such as unfavourable soil texture × shallow rooting depth (Terres et al., 2014). Similar results had also previously been reported by Thomasson and Jones (1989) who consequently suggested that "*the acceptance of land qualities, e.g. droughtiness and workability, which are strongly interactive between climate (weather) and soil*" are considered to improve land evaluation at regional scale. Therefore, interactions between marginality constraints were

also considered for each MAEZ. This issue is addressed in Chapter 3 (MALLIS development) since the relevance of interaction between constraints strongly depends on the MAEZ-specific constraint ranking.

Table 3: Agronomic synergy effects of relevant constraint combinations (adapted from Terres et al., 2014).

Criterion 1		Criterion 2		
Criterion	Sub-criterion	Criterion	Sub-criterion	Synergy
Low temperature		Excess soil moisture		-
Low temperature		Unfav. texture & stoniness	Heavy clay	-
Low temperature		Unfav. texture & stoniness	Organic soil	-
Dryness		Unfav. texture & stoniness	Stoniness	-
Dryness		Unfav. texture & stoniness	Sand, loamy sand	-
Dryness		Unfav. texture & stoniness	Heavy clay	-
Dryness		Rooting depth		-
Dryness		Poor chemical properties	Salinity	-
Dryness		Poor chemical properties	Sodicity	-
Dryness		Slope		-
Excess soil moisture		Unfav. texture & stoniness	Stoniness	=
Excess soil moisture		Unfav. texture & stoniness	Organic soil	-
Excess soil moisture		Rooting depth		-
Excess soil moisture		Slope		+
Unfav. texture & stoniness	Stoniness	Unfav. texture & stoniness	Sand, loamy sand	-
Unfav. texture & stoniness	Stoniness	Unfav. texture & stoniness	Heavy clay	=
Unfav. texture & stoniness	Stoniness	Unfav. texture & stoniness	Organic soil	+
Unfav. texture & stoniness	Stoniness	Rooting depth		-
Unfav. texture & stoniness	Stoniness	Slope		-
Unfav. texture & stoniness	Sand, loamy sand	Unfav. texture & stoniness	Heavy clay	=
Unfav. texture & stoniness	Sand, loamy sand	Unfav. texture & stoniness	Organic soil	+
Unfav. texture & stoniness	Sand, loamy sand	Rooting depth		-
Unfav. texture & stoniness	Sand, loamy sand	Poor chemical properties	Salinity	-
Unfav. texture & stoniness	Heavy clay	Rooting depth		-
Unfav. texture & stoniness	Heavy clay	Poor chemical properties	Salinity	-
Unfav. texture & stoniness	Heavy clay	Poor chemical properties	Sodicity	-
Unfav. texture & stoniness	Heavy clay	Poor chemical properties	pH	-
Unfav. texture & stoniness	Heavy clay	Slope		=
Unfav. texture & stoniness	Organic soil	Slope		=
Rooting depth		Poor chemical properties	Salinity	-
Rooting depth		Poor chemical properties	Sodicity	-
Rooting depth		Slope		-
Poor chemical properties	Salinity	Poor chemical properties	Sodicity	-

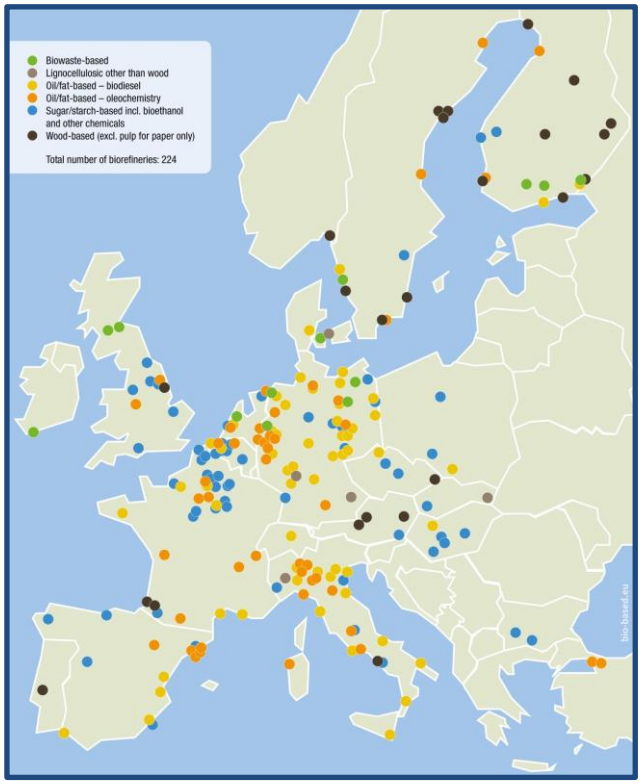

Figure 6: Biorefineries in Europe 2017 (modified from bio-based.eu).

In addition to the marginality factors defined by JRC, this study also considers other relevant marginality constraints such as environmental risks (Baulcombe et al., 2009; Thomasson and Jones, 1989), availability of local infrastructure and markets (Fig. 6), field accessibility and size of land holdings (especially relevant for Eastern Europe e.g. Romania (Popescu et al., 2016)). For this reason, three categories of marginality were classified (Table 2):

1. natural constraint-based marginality,
2. socio-economic/political limitations,
3. endangered sites.

Any of these could require specific changes in current management practices or combinations of practices in order to optimize the potential agricultural utilization of the sites within a MAEZ (ecological/environmental or economically oriented). Category 3 refers here to sites which are currently not marginal but which are in transition from arable to marginal due to inappropriate agricultural practices (Montanarella and Tóth, 2008; Zucca et al., 2014). This means endangered sites are currently productive but, if not managed properly, are at risk of being transformed into marginal lands in the long term. This could potentially be caused by a lack of know-how or a lack of awareness among farmers or within the government. Consequently, category 3 sites could potentially be transformed into category 1 sites. For example, southern Europe is facing the problem that arable lands are gradually being transformed into marginal lands due to inefficient management practices to control erosion (Cosentino et al., 2015). However, MAEZ mapping in WP 2 only focused on natural constraint-based marginality because there was a lack of sufficient and reliable data on socio-economic aspects. Thus, the natural constraints (Table 2, category 1) were grouped and mapped according to their relevance for each MAEZ.

The following sections (2.1.-2.7.) give a brief overview of each biophysical constraint category on which MAEZ mapping was based. Each section contains

1. a growth suitability ranking for each of the pre-selected industrial crops (Table 1) according to the constraint-specific parameter (because crop choice is the most important practice that all other management practices depend on),
2. the most relevant mechanisms by which plant growth can be limited for each constraint,
3. types or combinations of agricultural practices that can potentially enable these growth-limiting mechanisms to be overcome.

Where necessary, additional information about both the distribution of and the knowledge about relevant constraints in the Ukraine are provided because the Ukraine was not part of MAEZ development in Task 2.1-2.6 (Elbersen et al., 2018b, 2018a).

In the overview of agricultural practices in Tables 4 and 4ff, a ranking system (from -3 = strong negative effect to +3 = strong positive effect) illustrates how the constraints can be specifically met by the agricultural practices. The ranking system was based on expert opinion.

Table 4: Potential effects (ranking) of structured and systematic agricultural measures on agriculture facing biophysical constraints as selected by expert opinion; (from -3 = strong negative effect to +3 = strong positive effect).

				Biophysical constraints												
				Climatical				Soil / terrain								
Dimension	Category of measure	Method/ Strategy	Technique	Low temperature	High temperature	Dryness	Excessive moisture	Poor soil drainage	Unfav. texture / stoniness	Shallow rooting depth	Steep slope	Low soil fertility	Alkalinity	Acidity	Salinity	Other contamination
Structured measures	Irrigation	Surface irrigation	Line irrigation	-1	0	1	-3	-3	-1	1	-3	1	0	0	1	0
		Pressurized irrigation	Sprinkler irrigation	0	2	2	-3	0	2	1	1	1	1	1	1	0
			Microirrigation (drip irrigation)	0	0	3	-3	1	3	3	2	2	0	0	2	0
			Deficit irrigation technique	0	0	3	-3	1	2	2	3	3	1	1	-1	0
	Landscape management	Field arrangement	Terracing	0	0	0	0	0	0	0	3	0	0	0	0	0
			Field shaping / planting density & geometry	0	0	1	1	0	2	2	1	0	0	0	0	0
		Field surroundings	Hedges	1	0	0	1	1	0	0	1	0	0	0	0	0
			Water channel	-1	0	-3	2	3	0	0	-3	0	1	1	0	0
Systematic measures	Cropping-based measures	Temporal diversification	Catch/ cover crop	1	2	1	2	3	1	-1	0	1	0	0	1	1
			Crop rotation	0	0	1	0	1	2	1	-1	2	0	0	1	2
		Spatial diversification	Agroforestry system	0	0	1	2	2	2	1	3	2	2	2	0	2
			Intercropping	1	1	2	2	2	1	0	2	1	1	1	1	1
			Mixed cropping	1	1	1	2	1	2	0	1	2	1	1	1	1
Crop selection	Morpholo-gical traits	Rooting zone	Deep	1	2	3	2	3	-1	-3	2	1	1	1	1	0
			Shallow	1	0	-3	-1	-2	2	3	1	0	0	0	0	0
	Physiolo-gical traits	Photosynthetic pathway	C3	3	1	0	0	0	0	0	0	0	0	0	0	0
			C4	1	3	2	0	0	0	0	0	0	0	0	1	0
		Life cycle	Annual	0	0	0	-2	-3	0	0	0	1	0	0	1	1
			Biennial	1	1	1	1	1	0	1	1	2	0	0	1	1
			Perennial	2	1	3	2	2	1	2	2	3	1	1	2	1

Table 4ff: Potential effects (ranking) of management systems on agriculture facing biophysical constraints as selected by expert opinion; (from -3 = strong negative effect to +3 = strong positive effect).

				Biophysical Constraints												
				Climatic				Soil / terrain								
Dimension	Category of measure	Method/ Strategy	Technique	Low temperature	High temperature	Dryness	Excessive moisture	Poor soil drainage	Unfav. texture / stoniness	Shallow rooting depth	Steep slope	Low soil fertility	Alkalinity	Acidity	Salinity	Other contamination
Components of management system	Soil cultivation	Tillage	Full till	1	-2	-2	-3	-1	-1	-1	-3	-1	1	1	0	1
			Reduced till	-1	1	1	1	1	1	1	-1	1	0	0	0	1
			Precision tillage	3	2	2	0	2	2	1	1	2	0	0	0	1
			No till	2	3	3	2	1	2	2	3	2	0	0	0	0
		Mulching	Living mulch	1	-2	-2	3	1	1	-1	2	2	1	1	1	-1
			Cover soil with film	2	1	2	-1	-2	2	1	1	1	0	0	-1	-1
			Harvest residuals	2	-1	-1	0	1	1	-1	-3	2	1	1	0	-1
	Establishment/ planting material	Priming of seeds / planting material	Pesticides	1	0	1	1	2	1	0	0	1	1	1	1	0
			Micronutrients	1	1	1	1	1	2	1	0	3	0	1	1	-1
			Bio-stimulators	0	0	1	1	1	2	1	0	2	1	1	1	0
		Planting technique	Rhizomes	1	1	1	-1	0	1	1	1	1	-1	-1	0	0
			Plantlets	1	2	2	1	1	2	2	2	2	0	0	1	0
			Collars	1	2	2	-1	0	0	-1	1	1	-1	-1	-1	0
			Unrooted cuttings	1	2	0	2	1	0	-1	2	0	1	1	1	0
	Crop protection	Pest management measures	Pesticides	1	1	1	1	-1	0	0	2	1	1	1	1	0
			Biological pest control	1	0	0	2	2	2	0	1	1	0	0	0	0
			Crop rotation strategy	2	1	2	1	2	2	1	1	2	1	1	1	2
		Weeding	Mechanical	1	1	1	-1	0	-1	-1	-3	1	0	-1	-1	0
			Thermal	3	1	1	2	2	2	0	0	2	0	0	-1	0
			Chemical	1	1	1	0	-1	2	1	1	0	0	0	1	0
			Biological	2	1	-1	2	2	1	1	2	1	1	1	1	1
			Cover soil with film	2	1	1	0	0	2	2	2	-2	0	0	0	0
	Fertilization	Application technique	Broadcast	-1	1	1	-1	1	1	0	1	1	0	0	0	0
			Ground level	0	1	1	0	0	1	0	-1	1	0	0	-1	0
			Injection	1	2	1	0	2	0	-1	1	1	0	0	0	0
		Source	Organic fertilizer	2	3	3	-1	-1	2	1	2	3	2	2	2	3
			Liming	1	0	0	1	1	2	0	0	2	-1	3	-2	0
			Chemical fertilizer	1	1	1	-1	1	1	1	-1	3	-1	-1	-2	0
		Form	Solid	2	1	2	1	1	2	0	0	1	0	0	1	0
			Liquid	2	-3	-3	-1	1	1	0	0	1	0	1	0	0
		Time of application	Spring	-1	2	2	1	1	1	0	0	1	0	0	0	0
			Summer	-2	1	2	1	1	1	0	0	1	0	0	0	0
			Autumn	0	0	0	-1	1	0	0	1	-1	0	0	0	0
			Winter	0	0	0	-2	-1	0	0	-1	0	0	0	0	0
		Frequency of applications per year	one	1	-1	-1	1	1	-1	1	1	1	0	0	0	0
			> 1	1	1	1	-1	-1	1	-1	-1	2	0	0	0	0

2.1. Low temperature (insufficient thermal time) and high temperature

The European continent stretches over a large geographic area, ranging from 71°11'N in the north of Norway to 34°48'N in the south of Greece, and from 24°32'W in the west of Iceland to 68°18'E in the Ural Mountains. Hence, the near surface temperature varies considerably across Europe (Fig. 7). This renders temperature a major growth parameter to be considered for the development of low-input practices, because each crop has a certain temperature range, represented by a

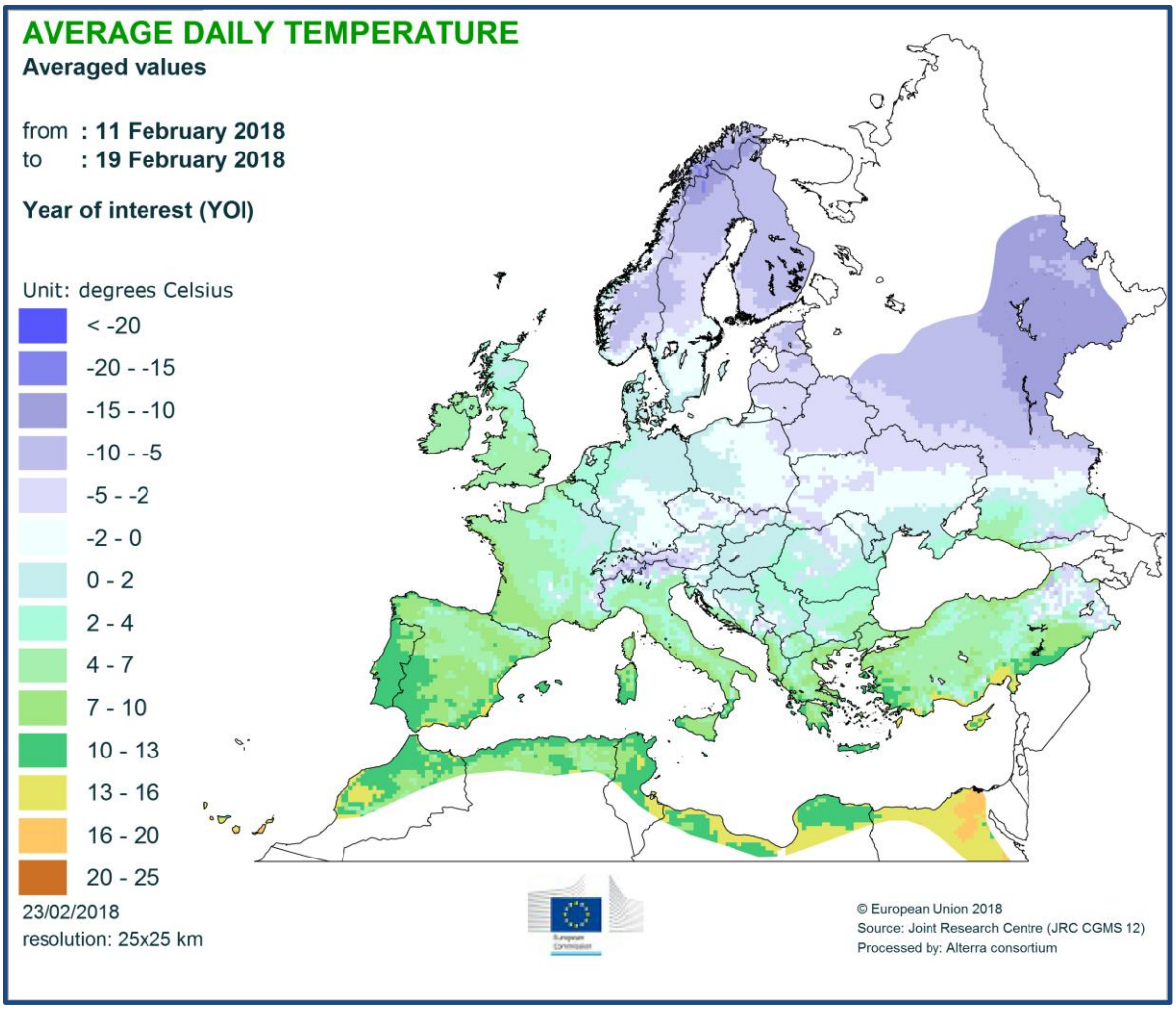

Figure 7: Distribution of average daily temperature across Europe in February 2018 (taken from JRC MARS Explorer, 2018)

minimum, a maximum, and an optimum for growth (Table 5). "*These climatic thresholds are mostly explained by the impact of temperature on enzymatic activities that regulate the rates of important plant physiological processes, such as photosynthesis and leaf* appearance *(Bonhomme, 2000).*" (Van Orshoven et al., 2014). In addition, Van Orshoven et al. (2014) state that "*growth rates and yields are maximized when crops are grown near the species-specific optimal temperature*

(T_{opt}) but gradually decrease at lower temperatures until the base temperature (T_b) is reached, at which no development occurs. Similarly, at temperatures higher than T_{opt}, development rates decline until a critical temperature (T_{crit}), near lethal levels (Hodges, 1990). Negligible growth occurs for most agricultural crops at temperatures below 5°C or above 35-40°C (Porter and Semenov, 2005)." Additionally, the length of the growing season (GS) determines whether a crop can complete its physiological life cycle (Van Orshoven et al., 2014) as required for the intended conversion route. This parameter can be best assessed by thermal time, which uses growth degree days (GDD, °Cd) as its functional unit (Van Orshoven et al., 2014). Thermal time is the sum of differences between daily average temperature (T_{av}) and T_b, assuming that $T_{av} > T_b$. In the approach proposed by JRC (Van Orshoven et al., 2014), the threshold defining GS as marginal for food crop production is set at ≤ 180 d (with T_b = 5 °C) or a thermal time ≤ 1500 °Cd.

Table 5: Crop-suitability ranking (from 0 = unsuitable to 4 =very suitable, whereas both 0 and 1 were defined as marginal) according to temperature. Classification adapted from Ramirez-Almeyda et al. (2017). Crop-suitability values were based on literature review and expert opinion.

	Temperature classes (°C) (taken from Ramirez-Almeyda et al., 2017 and extended based on expert opinion)					
Crop	**0-5**	**5-8**	**8-10**	**10-20**	**20-30**	**> 30**
Biomass sorghum	0	0	1	2	4	3
Camelina	3	4	4	4	3	2
Cardoon	0	0	1	3	4	2
Castor bean	0	0	1	3	4	4
Crambe	0	2	2	4	3	3
Ethiopian mustard	0	1	2	3	4	1
Giant reed	0	2	2	3	4	4
Hemp	0	2	2	3	4	1
Lupin	2	2	3	4	4	2
Miscanthus	0	2	2	4	4	1
Pennycress	3	4	4	4	2	1
Poplar	2	2	2	4	2	0
Reed canary grass	1	2	2	4	2	0
Safflower	0	0	0	1	4	3
Siberian elm	0	1	2	4	4	1
Switchgrass	0	2	2	4	4	1
Tall wheatgrass	0	1	3	4	3	0
Wild sugarcane	0	0	1	3	4	4
Willow	2	2	2	4	2	0

Thus, a careful selection of crops according to thermal conditions is the first step in developing optimized, site-specific, low-input practices, both to overcome any marginality constraints (Table 2) and enable low-input levels, in particular regarding fertilization, weeding, tillage and irrigation. Very low temperature and very high temperature limit or exclude the growth of agricultural crops. A low T_b allows some perennial or winter-annual crop species to still be able to develop well under low-temperature conditions (Table 7). This leads to both a longer vegetation period accompanied by a higher GDD compared to summer-annual crop species (Tables 2, 5-7). Conversely, many annual crop species, especially those with a C4 photosynthetic pathway, can grow well under high-temperature conditions because their active CO_2 assimilation performs better than in C3 plants when radiation and temperature are high and free-air CO_2 low enough (Sage et al., 2012; Sage and Sage, 2013).

Table 6: Crop-specific minimum thermal growth requirements based on literature review and expert opinion.

	Factors of thermal growth requirements		
Crop	Base temperature (°C)	Minimum length of growth season (d)	Minimum of growth degree days (thermal time, °C d)
Biomass sorghum	8	100	1500
Camelina	5	90	1000
Cardoon	7,5	120	1100
Castor bean	10	135	1500
Crambe	5	100	1200
Ethiopian mustard	5	120	2000
Giant reed	5	210	1843
Hemp	6	90	1400
Lupin	0	222	2260
Miscanthus	5	78	1700
Pennycress	4	90	1200
Poplar	0	180	2200
Reed canary grass	0	111	2000
Safflower	2	120	1800
Siberian elm	6	150	2000
Switchgrass	6	140	2060
Tall wheatgrass	4	90	1200
Wild sugarcane	10	210	2400
Willow	2	180	2000

However, even where temperature is not limiting according to Van Orshoven et al. (2014) (Table 2), there are relevant differences in thermal requirements of industrial crops,

including killing-frost tolerances (Table 5-7). In MAGIC, these different thermal requirements require a crop-specific ranking system to allow optimized, site-specific crop selection. Therefore, the temperature thresholds (T_b and T_{crit}) for each of the pre-selected crops (Table 5) were identified based on the literature (Clifton-Brown and Jones, 1997; FAO, 2007; Jing et al., 2012; Ramirez-Almeyda et al., 2017) and expert opinion. The ranking scale ranges from 0 (unsuitable) to 4 (very suitable), with intermediate values 1 (low suitable), 2 (medium suitable) and 3 (suitable). In line with Ramirez-Almeyda et al. (2017), the classes 0 and 1 were defined as areas marginal for the cultivation of a crop and therefore unsuitable for selection of this crop for low-input practices. Based on these rankings, the suitabilities of the industrial crops under the given thermal conditions of the MAEZs were compared (see Chapter 3).

Table 7: Crop-suitability ranking (from 0 = unsuitable to 4 =very suitable, whereas both 0 and 1 were defined as marginal) according to killing frost. Classification adapted from Ramirez-Almeyda et al. (2017). Crop-suitability values were based on literature review and expert opinion.

	Killing frost classes (°C)				
Crop	**< -20**	**-20 - -10**	**-10 - -5**	**-5 - 0**	**0-1**
Biomass sorghum	0	0	0	0	0
Camelina	2	2	2	3	4
Cardoon	0	0	0	2	3
Castor bean	0	0	0	0	0
Crambe	0	0	0	2	4
Ethiopian mustard	0	0	0	0	2
Giant reed	0	0	0	1	1
Hemp	0	0	0	0	0
Lupin	2	2	2	3	3
Miscanthus	0	0	2	2	3
Pennycress	2	2	2	3	4
Poplar	2	2	2	3	3
Reed canary grass	2	2	2	3	3
Safflower	0	0	0	0	1
Siberian elm	0	1	2	3	3
Switchgrass	0	2	2	2	3
Tall wheatgrass	0	1	2	3	3
Wild sugarcane	0	0	0	0	1
Willow	2	2	2	3	3

2.2. Dryness – Too dry conditions

Drought is very relevant for crop production, as the amount and distribution of rainfall throughout the growing seasons affects plant growth, development and yield.

Water participates directly or indirectly in all metabolic processes in living organisms. Excess water in the soil can injure plants through lack of oxygen, leading to oxygen stress by hypoxia or anoxia. On the other hand, limited amounts of water during plant growth causes water stress, in turn influencing physiological plant responses, such as photosynthesis, mainly through stomatal closure to restrict water loss by transpiration (Cosentino et al., 2016; Flexas et al., 2007; Lawlor and Cornic, 2002). Other typical symptoms of water stress include changes in cell growth, leaf expansion rate and other plant morphological processes (Cosentino et al., 2016; Sánchez et al., 2015).
Soil moisture availability is a measure of dryness, which depends on the rates of precipitation and potential evapotranspiration. The combination of low precipitation and high evapotranspiration leads to poor crop growth by limiting the moisture supply. According to Van Orshoven et al. (2014), dryness is calculated based on the ratio of annual precipitation (P) to annual potential evapotranspiration (PET). The threshold value for dryness proposed by JRC is 0.6 (P/PET ≤ 0.6). However, based on the expert judgement, the threshold value proposed by the JRC report was modified in MAGIC and set at 0.5 (P/PET ≤ 0.5). Uneven rainfall distribution and high reference evapotranspiration are typical conditions in Southern Europe.

In MAGIC, precipitation classes were developed based on yearly precipitations for perennial crops (mm/a) and growing season precipitation for annual crops (mm/growth season). These classes were classified from 0 to 4, as growing areas unsuitable (0), low suitable (1), medium suitable (2), suitable (3) and very suitable (4) for the selected crops (Table 8). For precipitation levels above 1000 mm the suitability values of the class 800 – 1000 mm were applied for mapping. In some cases, this may require a further (crop-specific) evaluation, because too high precipitation levels can also impede successful cultivation of a crop. Furthermore, the yield levels of the crops are expected to decline with decreasing precipitation levels in drought affected regions. Thus, annual crops such as camelina, crambe and Ethiopian mustard can complete their (relatively short) life cycle well even if the precipitation level during growth season is lower 100 mm (Table 8). However, their biomass yield level is much lower compared to other industrial crops which have both higher water demand and a longer growth period.

Table 8: Crop-suitability ranking (from 0 = unsuitable to 4 =very suitable, whereas both 0 and 1 were defined as marginal) according to precipitation. Classification adapted from Ramirez-Almeyda et al. (2017). Crop-suitability values were based on literature review and expert opinion.

	Precipitation classes (mm/a or mm/growth season for annuals)							
Crop	**0-100**	**100-200**	**200-300**	**300-400**	**400-500**	**500-600**	**600-800**	**800-1000**
Biomass sorghum	0	1	2	3	4	4	4	4
Camelina	3	4	4	4	4	4	2	2
Cardoon	0	0	0	1	2	3	3	4
Castor bean	1	2	2	3	3	4	4	4
Crambe	3	4	4	4	4	4	2	2
Ethiopian mustard	2	3	3	3	3	4	4	4
Giant reed	0	0	1	1	2	3	4	4
Hemp	0	1	2	3	4	4	4	3
Lupin	0	1	2	2	3	4	4	4
Miscanthus	0	0	0	0	1	2	3	3
Pennycress	1	1	2	4	4	4	4	4
Poplar	0	0	0	0	0	0	2	3
Reed canary grass	0	0	0	0	0	0	2	3
Safflower	0	1	2	3	4	4	4	3
Siberian elm	0	0	1	2	3	4	4	4
Switchgrass	0	0	0	1	2	3	4	4
Tall wheatgrass	0	0	1	3	4	4	4	4
Wild sugarcane	0	1	1	2	3	4	4	4
Willow	0	0	0	0	0	0	2	3

2.3. Limited soil drainage and excess soil moisture

The mechanisms of both limited soil drainage and excess soil moisture (water content above field capacity) have been concisely explained by Van Orshoven et al. (2014). Following their conclusions, excess soil moisture should be evaluated by adding up the number of days with soil moisture content exceeding field capacity (Van Orshoven et al., 2014). In this study, the threshold for severe excess soil moisture conditions for plant growth is 230 days (Table 2). Excess soil moisture conditions limit the oxygen supply in plant root zones impeding nutrient uptake (Reynolds et al., 2002). Sub-optimal cultivation systems further increase the risk of disease outbreak and environmental damage through nutrient leaching, GHG emissions and soil compaction. Limited soil drainage is a morphometric parameter indicating soil wetness for a longer period. According to Terres et al. (2014), limited soil drainage has three possible threshold criteria (Table 2). Both excess soil moisture and limited soil drainage strongly depend on climate (heavy rains) and geophysical conditions (landscape and soil type e.g. heavy clay). Instead of a crop-specific ranking, the following sub-sections provide some key information on both challenges and solutions for agriculture under conditions of limited soil drainage and excessive soil moisture.

2.3.1. Soil protection

Wet arable soils are highly susceptible to compaction when agricultural machinery with high axle load is used (Greenland, 1977; Schäfer-Landefeld et al., 2004). Soil compaction further impedes root development and increases the risk of erosion (Horn et al., 1995). Therefore, it is highly recommended to reduce soil compaction on wet soils wherever possible. The most promising strategy for reducing soil compaction is the conceptualization of a site-specific cropping system which allows a low intensity of traffic on the area for the various agricultural procedures such as tillage, sowing, crop protection, fertilization and harvesting. One major parameter of an optimized strategy is the selection of a suitable perennial crop: seen over the long term, perennial crop cultivation requires only a low level of soil disturbance through tillage and traffic (once successfully established) compared to annual crops. Especially on severely wet soils, the time windows for sowing, crop protection and harvest are short compared to normal soil conditions. Therefore, both the number and the type of establishment procedures should be tailored to reduce soil compaction. This can be ensured with woody crops. Woody crops can be established using unrooted cuttings (Carthy et al., 2018). In addition, the harvest of woody crops can be done in the winter when topsoil is frozen. This has two important advantages: (i) the potential soil compaction of traffic tends towards zero on frozen topsoil and (ii) the trafficability is much better than on non-frozen topsoil.

2.3.2. GHG mitigation

It is recommended to select cropping systems with a low nitrogen (N) fertilizer input level on sites with limited soil drainage or excessive wetness in course of GHG mitigation. Both the amount and timing of N fertilization can increase N_2O emissions by increasing water-filled pore space (Liu et al., 2015; Smith et al., 1998). N_2O emissions play a key role in GHG mitigation because N_2O is one of the most relevant greenhouse gases in agriculture (Snyder et al., 2009). Additionally, low levels of N fertilization increase the need for high efficiency in fertilizer application techniques. The efficiency of fertilizer application can be increased using precision farming concepts such as sensor-controlled nitrogen application (Obenauf et al., 2014; Reckleben, 2014) in combination with the use of site-specific management zones (C. W. Fraisse et al., 2001). However, low soil trafficability may impede the use of heavy machinery over the growing season. Therefore, the applicability of precision farming should be evaluated site-specifically (see Chapter 2.3.1.). Alternatively, agroforestry systems which include legumes may be a suitable solution provided these ensure a sufficient uptake of atmospheric N via rhizobacteria (Gualtieri and Bisseling, 2000).

However, the choice of low-demanding industrial crops is a major step towards an optimal MALLIS in limiting conditions due to poor drainage or excessive wetness. Woody crops, such as willow, Siberian elm and poplar (Carthy et al., 2018), and perennial grasses such as miscanthus have shown good and stable agronomic performance under severe growth conditions of limited soil drainage or excessive wetness. Conversely, the cultivation of annual crops can only be recommended under certain conditions such as the applicability of reduced or no till cropping system. In general, it is to be discouraged because of the soil protection and workability aspects described above.

2.4. Unfavourable soil texture and stoniness

Unfavourable soil texture, e.g. a high proportion of clay or sand, poses a major threat to crop production. Soils with a clay content of more than 50 % have high water retention, but mostly this water is bound and inaccessible to plants (Shykula et al., 2004). When wet, these soils can be sticky and water resistant, besides, they are poorly aerated (poor air permeability). Due to high clay content, the content of nutrients in such soil is also very high, but when getting dry, clay requires additional compacting around the seeds (or roots), which in turn can cause plant wilting. The low porosity of heavy clay also restricts water movement leading to surface water accumulation when rainfall is high. In addition, they can damage root growth during wet seasons due to their shrink-swell capacity. Any agricultural treatments are complicated when clay soil is wet, due to the sticking of clay to the working bodies and imposing the danger of soil compaction (Zinchuk and Zinchuk, 2006). Thus, soils with high clay content decrease the soil workability, especially during wet seasons, by limiting the access of machinery (Alakukku et al., 2003).

From the agronomic point of view, valuable soil must have granular structure with the size of aggregates from 0.25 to 10 mm. Clay soils belong to the category of so-called unstructured soil, i.e. containing less than 40% of air-dry aggregates in the range from 0.25 to 10 mm and less than 20 % hydrophobic aggregates (Plisko, 2004). Consequently, such soil has poor air permeability, which leads to insufficient oxygen supply to plant roots and soil microbiota. The lack of a developed capillary system in the soil also reduces the available to plants moisture. Insignificant moisture content makes it hard for plants to uptake nutrients from the soil because plant root system is able to absorb only those nutrients that are in dissolved form (Medvedev, 2009).

When growing industrial crops on hard clay soils (In Ukraine, there are 2.61 million hectares of agricultural land characterized by high clay content) it is crucial to provide optimal aeration and soil density (Nadtochii et al., 2010). In addition, weed control is important because weeds have an advantage in growth and development on such soils. Many weed species capable of fast sprouting from topsoil and they grow more intensively than crops. Ensuring a sufficient plant cover contributes to good rooting, which in turn positively affects the changes in soil structure and improves its agrophysical characteristics.

On sandy soils, crop management practices such as fertilization and irrigation have poor efficiency due to low soil fertility and low water-holding capacity, respectively (Van Orshoven et al., 2014, 2012). The use of green manure or compost increases the soil water-holding capacity, thus enhancing soil structure.

Soils comprised of coarse fragments have negative impacts on plant growth as they affect the soil workability. In addition, a high proportion of stones can lead to the space required for rooting being insufficient and this subsequently affects uptake of water and nutrients. The presence of stones and rocks at the soil surface negatively affects crop growth by impeding seed germination. It also limits the use of agricultural machinery for cultivation practices. The threshold is set a ≥ 15% surface cover (Van Orshoven et al., 2014) (Table 2).

Another soil category which impedes plant growth is labelled 'organic soils'. These soils do not provide a sufficient foothold for roots, which is particularly relevant for perennial crops. They have a high organic matter content ≥ 30% in a layer of 40 cm or more, either extending down from the surface or taken cumulatively within the upper 100 cm of the histic horizon, (IUSS Working Group WRB, 2006). However, peatlands are very valuable for their ecological functions. Cultivation of such soils requires drainage, which causes oxidation of peat and CO_2 release. Thus, for sustainability reasons, these soils are not used for crop cultivation.

Table 9: Crop-suitability ranking (from 0 = unsuitable to 4 =very suitable, whereas both 0 and 1 were defined as marginal) according to soil texture. Classification adapted from Ramirez-Almeyda et al. (2017). Crop-suitability values were based on literature review and expert opinion.

	Soil texture classes				
Crop	Sand (coarse)	Loam (medium-medium fine)	Clay (fine)	Heavy clay (very fine)	Peat (no mineral texture)
Biomass sorghum	0	4	4	3	0
Camelina	3	4	3	2	2
Cardoon	2	4	2	0	0
Castor bean	3	4	4	3	0
Crambe	3	3	4	3	2
Ethiopian mustard	3	4	1	0	0
Giant reed	2	4	3	2	0
Hemp	1	4	3	1	1
Lupin	4	4	3	2	0
Miscanthus	1	4	3	2	1
Pennycress	3	3	3	2	2
Poplar	1	4	2	1	2
Reed canary grass	1	4	2	1	0
Safflower	2	4	4	2	0
Siberian elm	3	4	2	1	0
Switchgrass	2	4	2	0	0
Tall wheatgrass	3	4	2	1	0
Wild sugarcane	2	4	3	2	0
Willow	2	4	2	1	1

2.5. Shallow rooting depth

Another challenge for crop growth under marginal conditions is shallow rooting depth, which is defined as the depth (cm) from soil surface to coherent hard rock or hardpan. Cultivation practices and suitability of an area for crop production largely depend on the volume of rootable soil. This is defined by physical and chemical components of the soil and therefore determines the access of crops to soil nutrients and water. In the mapping of marginal lands for the cultivation of industrial crops, a shallow depth from the soil surface to an impeding layer (hardpan) or to bedrock (30 cm or less in Leptosols) is considered marginal. Soil depth classes were developed according to crop-specific requirements (Table 10). Optimized cropping systems on shallow soils need to include both crops with a shallow rooting system and cultivation techniques with a low level of soil disturbance, e.g. no till and weeding by covering the soil with foil (Table 4ff). The suitability of spatial diversification measures such as legume intercropping or other types of mixed cropping strongly differs between the main crops (Von Cossel et al., 2017).

Table 10: Crop-suitability ranking (from 0 = unsuitable to 4 =very suitable, whereas both 0 and 1 were defined as marginal) according to soil depth. Classification adapted from Ramirez-Almeyda et al. (2017). Crop-suitability values were based on literature review and expert opinion.

	Soil depth classes (cm)			
Crop	**Shallow (<35)**	**Moderate (35-80)**	**Deep (80-120)**	**Very deep (> 120)**
Biomass sorghum	1	2	3	4
Camelina	3	4	4	4
Cardoon	0	1	2	4
Castor bean	2	3	4	4
Crambe	3	4	4	4
Siberian elm	0	2	3	4
Ethiopian mustard	0	1	2	4
Giant reed	1	2	3	4
Hemp	0	1	2	4
Lupin	1	3	4	4
Miscanthus	0	2	3	4
Pennycress	3	4	4	4
Poplar	0	2	3	4
Reed canary grass	0	1	3	4
Safflower	2	3	4	4
Siberian elm	0	2	3	4
Switchgrass	0	2	3	4
Tall wheatgrass	2	4	4	4
Wild sugarcane	1	2	3	4
Willow	1	3	4	4

2.6. Poor chemical properties (Soil salinity, acidity and fertility)

Adverse chemical conditions comprise factors such as excess salts or toxic elements, which not only affect plant growth but also pose health risks. Excess salts impact plant growth by increasing osmotic pressure and reducing water availability. An excess of salts can be described as 'salinity' (excess of free salts) or 'sodicity' (saturation of the soil exchange complex with sodium), (Mantel and Kauffman, 1995). The following two sections describe mechanisms, thresholds and measures to overcome soil salinity and soil acidity.

2.6.1. Salinity and sodicity

In Magic, salinity was identified using European soil maps (European Soils Database ESDAC) which were generated in the ESDAC project (Panagos et al., 2012; Tóth et al., 2008). Solonchaks soil 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^{-1}). In MAGIC, soil salinity classes of EU-28 were developed and crops ranked according to their salinity tolerance (Table 11).

Table 11: Crop-suitability ranking (from 0 = unsuitable to 4 =very suitable, whereas both 0 and 1 were defined as marginal) according to soil salinity. Classification adopted from Ramirez-Almeyda et al. (2017). Crop-suitability values were based on literature review and expert opinion.

	Classes for salinity (dS m^{-1})					
Crop	**<2**	**2-4**	**4-10**	**10-15**	**15-30**	**>30**
Biomass sorghum	3	2	0	0	0	0
Camelina	1	2	0	0	0	0
Cardoon	4	3	1	0	0	0
Castor bean	1	2	0	0	0	0
Crambe	2	3	1	0	0	0
Ethiopian mustard	3	2	0	0	0	0
Giant reed	4	3	1	0	0	0
Hemp	3	1	0	0	0	0
Lupin	4	4	3	2	1	0
Miscanthus	4	4	2	1	0	0
Pennycress	1	2	0	0	0	0
Poplar	4	3	2	1	0	0
Reed canary grass	4	3	2	0	0	0
Safflower	3	1	0	0	0	0
Siberian elm	4	4	2	0	0	0
Switchgrass	4	4	2	1	0	0
Tall wheatgrass	4	4	3	1	0	0
Wild sugarcane	4	3	3	1	0	0
Willow	4	3	2	1	0	0

Sodic soils are defined as soils with a sodium saturation of the exchange complex (ESP) greater than 15%. For EU-28, sodicity was mapped from the same source as salinity (ESDAC). It was identified from mapping units with more than 50% area of sodic soils (Solonetz) and soils with a sodic qualifier. In Ukraine, the total area of sodic soils amounts to 1.92 million hectares located mainly in the Steppe zone. Of these, 1.71 million hectares are still used in agriculture (Baliuk et al., 2012a). The meteorological conditions of the zone of sodic soil in Ukraine are characterized by a moderately continental climate with a dry and hot summer with the shade temperature often exceeding +40°C and periodic droughts. A precipitation-evaporation ratio usually is <1 (Kazakov et al., 2000; Novikova, 2009). Thus, high yield from sodic soils in the Ukraine can only be ensured under irrigation (Pyurko et al., 2000).

Both the chemical composition and the concentration of salts determine the characteristic plant diversity on such lands (sodic soils). The main cause of poor growth and wilting plants on sodic soils is the deficit of potassium and calcium along with imbalance of phosphorus metabolism caused by excess Na+ and Cl- ions in plant tissues (Grigoryuk et al., 1999; Raznopolov and Pyurko, 2000). Sodicity, on one hand, disrupts osmotic balance of the plant cells, which negatively affects water regime of plants, and on the other hand, creates a toxic effect of Na+, SO42- and Cl- ions on the physiological and biochemical processes in cells, specifically enzyme activity, and photosynthesis intensity (Novikova, 2004). However, some researchers believe that damage to plants is a consequence of the not direct toxic action of salts, but the accumulation of toxic products of altered metabolism in plants, primarily nitrogen metabolism (Raznopolov and Pyurko, 2000; Tyshhenko et al., 2013).

Depending on the degree of soil salinity, the reduction in yield may vary. To illustrate, weak degree of sodicity may cause a decrease in yield by 5-20 %, moderate by 20-30 %, and severe by 30-50 % (Romashhenko and Baliuk, 2000). The most effective methods of sodic soils reclamation are the following: washing with large quantities of fresh water, desalting reclamation, growing plants that accumulate significant amounts of salts (phytoremediation) and growing salt-resistant plants.

In addition to salinity and sodicity, other naturally occurring toxicities can potentially affect plant growth, for example aluminium toxicity in acid subsoils. High acidity, high sulphur availability and aluminium toxicity pose a great threat to crop production. However, due to data limitations, aluminium toxicity is not considered in the mapping. Acid sulphate soils become extremely acidic once they are drained because sulphides react with oxygen to form sulfuric acid. These soils are identified through the thionic qualifier of soils in the European Soils Database.

2.6.2. Soil acidity / Soil fertility

Soil acidity, expressed as soil pH, plays a key role in soil fertility. Soil fertility is defined as the availability of nutrients for crops and depends on a number of factors including changes in nutrient availability over time, soil type (Fig. 8) and crop-specific capacity of root-mediated pH changes in the rhizosphere (Hinsinger et al., 2003). For example, sandy soils have low nutrient levels and are therefore termed soils of low fertility. The availability of plant nutrients depends on soil reactivity, of which soil pH is a good indicator (Fig. 8).

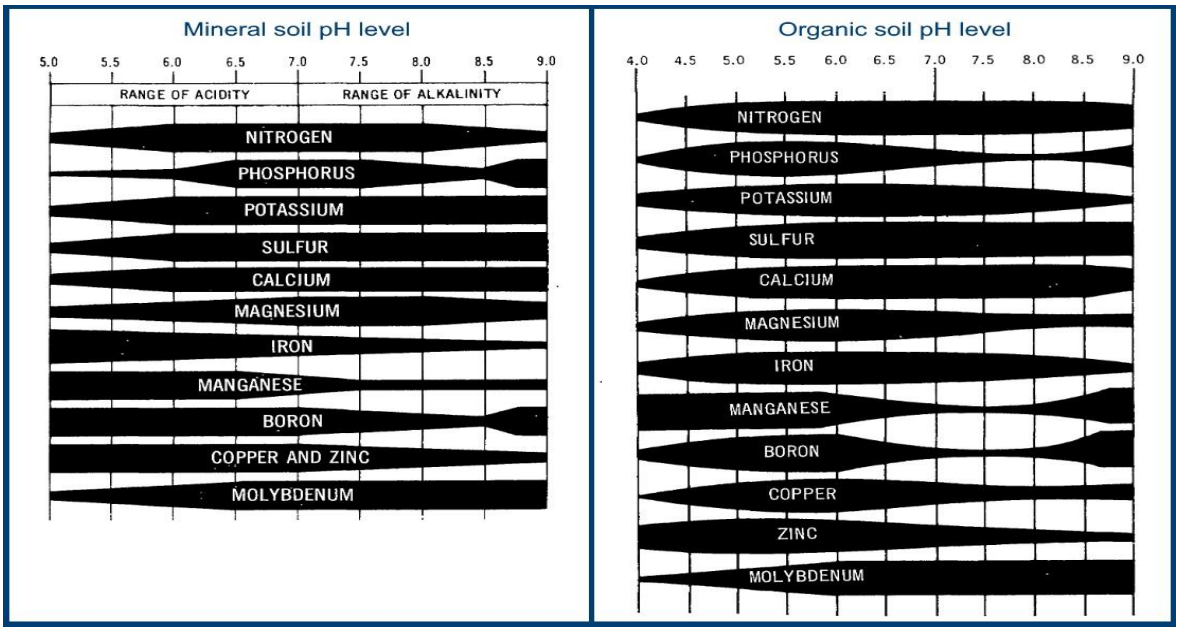

Figure 8: Availability of plant nutrients at different pH levels for a mineral soil (Pettinger, 1935) and an organic field soil (Lucas et al., 1961) (taken from Peterson, 1982).

Acidic soil conditions are most common in humid climates due to the natural acidification of soils following permanent leaching of carbonate fractions (Breemen et al., 1983). Acidity causes a complex deterioration of physical, chemical, biological, and agronomic characteristics of soil (Mazur, 2008). Under such conditions, peptization of colloids occurs, which leads to further destruction of the soil structure (Baliuk et al., 2012b). Furthermore, plant growth and root system development are suppressed, which affects the winter hardiness and drought tolerance, especially in perennial crops (Poliovyi, 2007). Soil acidity reduces the availability of nitrogen and phosphorus fertilizers and inhibits the activity of nitrogen-fixing bacteria (Veremeinko et al., 2013). In addition, fungal microflora actively propagates resulting in increased damage to plant by fungal diseases. "*In acid soils microorganisms do not function effectively. The activity of decomposer organisms and nitrogen fixing bacteria start declining when soil pH falls below 6.0 (Spies and Harms, 1988). Lower (acid) pH values indicate soil conditions that may limit crop yield*" (Terres et al., 2014).

Therefore, the regulation of soil pH is a relevant practice for improving growth conditions in severely acidic soils. This can be done through the application of lime-fertilizer. Depending on the type and amount of lime applied, this induces an increase or maintenance of the soil pH value and improves or stabilizes plant growth conditions in the short- to mid-term (Haynes and Naidu, 1998). In addition, weed infestation of fields can increase on acidic soils because the vast majority of weeds can withstand soil acidity. Consequently, technologies for the growing industrial crops on acid soils should be aimed at proper weed control, ensuring proper mineral nutrition nutrients and preventing further destruction of the soil structure.

For severely alkaline soil conditions, there is very little information on agricultural practices for pH regulation other than the selection of tolerant crops. However, the application of Fe fertilizers (e.g. $FeSO_4$) or other micronutrients (Fig. 8) can be an efficient short-term measure to improve the performance of industrial crops on alkaline soils (Hergert et al., 1996).

In this study, two parameters, soil pH and soil organic content (SOC), were chosen for the mapping of soil fertility. A topsoil pH (0-30 cm) of ≤ 4.5 or ≥ 8 was considered severely limited. The sub-severe threshold of topsoil acidity was set at ≤ 5.5 (Terres et al., 2014). It was shown, that the list of pre-selected industrial crops in Table 1 includes crops suitable for both severely acidic and alkaline soils (Table 12). The selection of an adequate industrial crop should be combined with a fertilization strategy aiming to (i) improve soil pH conditions and (ii) replenish those macronutrients that are in undersupply (Fig. 8). In addition, it is important to evaluate SOC as part of soil fertility because soil organic matter acts as a nutrient reservoir (Haynes and Naidu, 1998). Soils with low SOC have a poor buffering capacity and are thus referred to as soils of low fertility. The threshold for marginal conditions was set at < 0.5% SOC. Here, no crop-specific ranking was developed. Instead, low-input practices (other than crop-selection) were considered relevant for SOC enrichment including organic fertilizers, living mulch, harvest residues and the prioritization of perennial cropping systems.

In Ukraine, 17 % of arable land (3.7 million hectares) is acid soil with a pH varying from 5.0 to 5.5 (National report on the state of technogenic and natural safety in Ukraine, 2010).

Table 12: Crop-suitability ranking (from 0 = unsuitable to 4 =very suitable, whereas both 0 and 1 were defined as marginal) according to soil acidity. Classification adapted from Ramirez-Almeyda et al. (2017). Crop-suitability values were based on literature review and expert opinion.

	Soil acidity classes (pH)					
Crop	**0-4**	**4-4.5**	**4.5-6**	**6-7**	**7-8**	**>8**
Biomass sorghum	0	1	3	4	4	3
Camelina	0	2	3	4	4	3
Cardoon	0	0	2	4	3	4
Castor bean	0	3	4	4	4	3
Crambe	0	2	3	4	4	3
Ethiopian mustard	0	0	4	4	2	2
Giant reed	0	1	2	4	4	4
Hemp	0	0	1	4	3	3
Lupin	0	2	4	3	2	1
Miscanthus	0	1	3	4	2	1
Pennycress	0	2	3	4	4	3
Poplar	0	1	2	4	3	2
Reed canary grass	0	1	3	4	2	1
Safflower	0	1	3	4	4	3
Siberian elm	0	1	4	4	3	1
Switchgrass	0	1	3	4	3	1
Tall wheatgrass	0	3	4	4	3	1
Wild sugarcane	0	1	2	4	4	4
Willow	0	1	2	4	3	2

2.6.3. Contaminated soil

Soil contamination of agricultural land around industrial cities, in industrial zones, and places of former agrochemical warehouses by the most environmentally hazardous chemical elements (lead, cadmium, mercury, copper, zinc) sometimes exceeds the maximum permissible concentrations (MPCs) 5-15 times. Consequently, growing industrial crops on such lands leads to accumulation of these hazardous chemicals in the harvest. Recently, the tendency of abrupt exceeding MPCs in plant products has been observing, specifically, the content of lead in some production batch appears to exceed MPC by 0.1-0.6 mg/kg, zinc by 0.09-0.4 mg/kg, copper by 0.08-0.3 mg/kg, and cadmium by 0.06-0.8 mg/kg (National report on the state of technogenic and natural safety in Ukraine, 2010). As a rule, ions of heavy metals in soil are included in organic substances, carbonates, oxides of aluminum, iron, manganese, chromium, tin, silicon, and cobalt located in the 0-15 cm layer. High concentrations of these elements are capable of suppressing the growth and development of all plants without exception, as well as of soil microbiota (Evgrashkina, 2003).

Research results show that the application of humic acids can alter the uptake of mineral substances and minor nutrients by plants, and thus prevent excessive accumulation of nitrates in plants. Humic acids bind technogenic pollutants (compounds of mercury, lead) and prevent their uptake by plants. The group of soil biofilms, i.e. chemical elements and substances that can accumulate in living organisms in much larger concentrations than in the environment, includes cobalt, copper, zinc, and nickel. They have the property to accumulate in the organic compound of soil, therefore, with the increase in the content of organic matter in the soil the content of hazardous elements increases as well (Alekseenko, 2000).

There is growing literature on phytotherapy, i.e. growing energy crops (for example, miscanthus) as a way of soil purification from heavy metals. After all, biofuel plants are capable of forming significant biomass while growing on marginal soils (Kharchenko et al., 2013). At the same time, other researchers propose to use humic acids and micronutrients to reduce the uptake of heavy metals by plants (Smirny et al., 2006). This research field is relevant since biomass with a high content of heavy metals must be converted into energy with additional safety measures and cannot be a commodity. However, human induced soil contamination was not considered for mapping due to a lack of available data.

2.7. Adverse terrain (steep slope and erosion affected sites)

Adverse terrain is an important constraint category to be considered in the mapping of marginal lands. Adverse terrain is mainly characterized by steep slope conditions. Sloping land renders it difficult to carry out crop cultivation practices using large agricultural machinery. As sloping land is at high risk of erosion, leading to land degradation, it is important to provide these soils with vegetation cover. This not only helps to control runoff but also increases water infiltration. Slope is described as the change of elevation with respect to planimetric distance (%). Slopes of ≥ 15% are considered severely limiting and those of 12% - 15% are rated as sub-severe (Van Orshoven et al., 2014).

In these marginal areas, special attention should be paid to avoiding deep soil tillage, cultivation of annual crops, and lack of surface water control. Vegetation cover plays a significant role in regulating hydrological processes and changing soil properties. Perennial crops can help mitigate the erosion risk as soil tillage is only carried out during establishment, the soil is covered for a long period, and the release of organic residues enhances soil organic matter content. If annual crops are cultivated, conservation tillage, such as reduced tillage or no-till, should be applied, particularly if seeds are sown in periods of severe precipitation (e.g. autumn in southern Europe). The following classes of crop suitability for sloping areas were developed (Table 13).

Table 13: Crop-suitability ranking (from 0 = unsuitable to 4 =very suitable, whereas both 0 and 1 were defined as marginal) according to terrain (slope). Classification adapted from Ramirez-Almeyda et al. (2017). Crop-suitability values were based on literature review and expert opinion.

	Slope classes (°)					
Crop	**< 4**	**4-8**	**8-12**	**12-15**	**15-25**	**> 25**
Biomass sorghum	4	3	2	1	1	0
Camelina	4	3	2	2	1	1
Cardoon	4	3	2	2	1	0
Castor bean	4	3	3	2	1	1
Crambe	4	3	2	2	1	1
Ethiopian mustard	4	3	2	2	1	0
Giant reed	4	3	2	2	1	1
Hemp	4	2	1	1	0	0
Lupin	4	4	3	2	1	0
Miscanthus	4	3	2	2	1	1
Pennycress	4	3	2	2	1	1
Poplar	4	3	3	2	2	1
Reed canary grass	4	3	2	2	1	0
Safflower	4	3	2	1	1	0
Siberian elm	4	3	2	1	1	0
Switchgrass	4	3	2	2	1	1
Tall wheatgrass	4	3	2	1	1	0
Wild sugarcane	4	3	2	2	1	1
Willow	4	3	2	1	1	0

In Ukraine, 32 % of the total agricultural land (13.3 million hectares) is damaged by water erosion. Of these, 68 000 hectares completely lost their organic topsoil. At the same time, more than 6 million hectares are exposed to the impact of wind erosion, especially in the regions of the Southern Steppe with dust storms accounting for 159 days a year (National report on soil fertility in Ukraine, 2010). Average annual soil losses from water and wind erosion in Ukraine make up about 740 million tons of fertile soil, which contains about 24 million tons of organic matter, 0.7 million tons of mobile P, 0.8 million tons of K, 0.5 million tons of N and large amounts of minor nutrients (Smirnov, 2007). Erosion processes significantly decrease the availability of soil organic matter. Thus, the content of organic matter in slightly eroded chernozem decreases by 5-10 %, moderately eroded by 25-30 %, and severely eroded by 35-40 % in comparison with full chernozem (Svetlichnyi et al., 2004). Consequently, strategies for growing industrial crops on eroded lands should stipulate minimum soil tillage, weed control with the aid of mulch and agrotextile, and provide plants with sufficient amount of mineral nutrients to create favourable conditions for the powerful root system.

3. Definition and methodology of MALLIS development

In this chapter, the definition of best-practice low-input management systems for all selected industrial crops (see Task 4.1) is elaborated based on the consortium's expertise and on literature review. This ties in with current knowledge on best low-input agricultural practices for food crop production on good soils. The concept of best-practice low-input agricultural cropping systems considers management approaches from many categories of agricultural production, including organic, integrated, conservation agriculture and mixed crop-livestock farming. These all have one constant: low-input agricultural practices seek to optimize the use of on-farm resources while minimizing off-farm resources. This translates into having a more 'closed' production cycle (and, consequently, less external inputs) and requires more advanced agronomic skills.

Agronomic strategies for the successful application of low-input agricultural practices in a crop management system should be seen as a set of strategies that take into account both the interactions between soil, plants, atmosphere and also the optimal use of inputs in order to achieve the highest output with minimal (on-farm and/or off-farm) input supply. Agronomic strategies for low-input systems may also match good agricultural practices - cultivation practices that address environmental, economic and social sustainability for on-farm processes that result in safe and quality food and non-food agricultural products. Such practices include soil management in a way that maintains or improves soil organic matter, implementation of appropriate crop rotations, manure application, pasture management and other land-use practices as well as rational mechanical and/or conservation tillage practices. Diversity in crop rotations is a way to control pests and weeds, reduce reliance on synthetic chemicals, prevent soil-borne diseases, maintain soil fertility and reduce soil erosion, leading to off-farm inputs reductions. Reduced soil tillage, as in conservation agriculture, is a way to increase soil fertility, reduce soil erosion, increase organic matter and improve water buffer capacity. Water management is a big challenge in Common Agricultural Policy (CAP) and requires the adoption of techniques to monitor crop and soil water status, accurately schedule irrigation, etc. Fertilizers and agrochemicals should be applied in a balanced fashion, with appropriate methods and equipment and at adequate intervals to replace nutrients extracted by harvest or lost during production. Crop protection should be done in a way that maximizes the biological prevention of pests and diseases, in particular by promoting integrated pest management (IPM) and though appropriate rates and timings of agrochemicals. Preventive crop protection can also be supported by the

selection of resistant cultivars and varieties, crop sequences, crop associations (e.g. intercropping), and proper cultural practices.

The low-input agricultural practices to be identified here will be adapted to the marginality factors in order to effectively shape the new field trials (Tasks 4.3 & 4.4) and generate the necessary additional data to support the profitable cultivation of the crops on marginal lands (input to WPs 5-7). This chapter starts with a definition of MALLIS (Section 3.1.), followed by a methodological description of MALLIS development (Section 3.2.), and then considers the individual selection of low-input agricultural practices and their application in (i) the specific MAEZ as identified by work package 2 (Elbersen et al., 2018b) (3.3.1.) and (ii) the new field trials to be established in MAGIC.

3.1. Definition of MALLIS

The development of "marginal land low-input systems", referred to as "MALLIS" (for definition, see Box 4.1.4), is based on the definition of low-input practices elaborated in Section 1.2. (Box 4.1.3). The implementation of MALLIS should enable farmers to cultivate

Box 4.1.4 Definition of marginal land low input systems (MALLIS)

In the MAGIC project, MALLIS is defined as a set of low-input practices which are relevant management components to form viable cropping systems on marginal lands under specific climatic conditions and are sustainable in both socio-economic and environmental terms.

industrial crops on marginal lands, considering both economic and environmental aspects. Consequently, MALLIS should not only allow for profitable net farm income under the challenging biophysical growth conditions of marginal lands, but also help to (i) reduce off-farm inputs such as synthetic fertilizer, pesticides and energy (e.g. for water pumps, fuel, crop harvest machinery, storage, processing etc.) and (ii) mitigate negative macro-economic externalities (GHG emissions, biodiversity loss, ground- & surface water contamination, soil organic matter loss, erosion, degradation, land-use change), while (iii) ensuring feasible economic benefits at farm level. Therefore, the development of MALLIS considers not only the biophysical constraints but also socio-economic and ecological demands of the respective areas (Box 4.1.4).

3.2. Methodology of MALLIS development

MALLIS were developed for the pre-selected industrial crops (Table 1) to be grown on the most prevalent marginal agro-ecological zones (MAEZ) (Box 4.1.5). These MAEZ were identified and presented in Deliverable 2.6 (Elbersen et al., 2018a), whereas for some MAEZ more than one potentially limiting constraints were clustered in constraint categories (Table 14) according to Van Orshoven et al. (2014). Section 3.2.1 describes the main results. Section 3.2.2. gives a broad overview of crop-specific growth suitability of the pre-selected industrial crops (Table 1) for all MAEZ identified for Europe. Then the selection of potentially best performing crops based on the results of the multi-criteria analysis is described (Task 1.3) (3.2.3.).

Box 4.1.5 Definition of marginal agro-ecological zones (MAEZ)

A MAEZ is the combination of biophysical limitations and a climatic zone. In MAGIC, the biophysical limitations were adapted from Van Orshoven et al. (2014) (Table 2, category 1) but for each MAEZ only the most prevailing constraint factors were taken into consideration. In MAGIC, only the most relevant agro-ecological zones (AEZ) were chosen for MAEZ identification. These are: the Mediterranean (AEZ 1), the Atlantic (AEZ 2) and the Continental (AEZ 3), all of which represent more than 1 environmental zone (Fig. 5).

Once the MAEZ had been defined, the conceptualization of MALLIS development always began with the selection of most promising crops, because all other agricultural practices (tillage, fertilization, weeding, irrigation etc.) strongly depend on the type and site-specific performance of the crop. This MAEZ-specific growth-suitability ranking (and mapping) of the pre-selected industrial crops was based on the crop-suitability rankings presented in Chapter 2. After the identification of suitable crops, the conceptualization of MALLIS for MAEZ was done on a general level (regional scale), since detailed best practice recommendations for optimized management of agricultural practices very much depend on local conditions (field-to-farm scale). The MALLIS for the new field trials within MAGIC (field-to-farm scale) were developed under consideration of three main MAEZ criteria:

1. The crop's performance according to site-specific climatic and geographic conditions, especially under given biophysical constraints;
2. The kind and quality of biomass required in terms of given infrastructure, processing industries and distribution channels (markets);
3. The agricultural status of the farm(s), e.g. the techniques, knowledge and resources available to ensure successful cultivation of the crop.

Table 14: Overview of data used for MAEZ development in WP2 (Task 2.1 & 2.2) (taken from Elbersen et al., 2018a).

Constraint category	Sub- factor	Description	Selection based on (JRC, Meuncheberg, other...)	Threshold for marginal lands	Data source used for mapping
Adverse climate (Climate, CL)	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
	Dryness	Ratio of the annual precipitation (P) to the annual potential evapotranspiration (PET). Thresholdlimit: (P/PET ≤ 0.6)	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
Excessive wetness (Wetness, WT)	Excess soil moisture	Water content in the soil exceeds field capacity for at least 210 days (7 months)	JRC (Van Oorschoven et al, 2014)	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
	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	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
Adverse chemical conditions (Chemical, CH)	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	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
	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	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
	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
	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
Low soil fertility (Fertility, FE)	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)	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

Constraint category	Sub- factor	Description	Selection based on (JRC, Meuncheberg, other...)	Threshold for marginal lands	Data source used for mapping
	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
Limitations in rooting (Rooting, RT)	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 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
	Coarse fragments 7 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 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
	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
	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 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
Adverse terrain conditions (Terrain, TR)	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
	Flood risk	Risk of flooding in relation to risk of damage to the field and to crops during the growing season	Meuncheberg 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

3.2.1. The identification of prevailing MAEZ

In MAGIC, WP2 (Task 2.1 & 2.2) “marginal” land in Europe (EU 28) has been mapped (Elbersen et al., 2018b) according to the biophysical limitations defined and classified by JRC (Terres et al., 2014; Van Orshoven et al., 2012, 2014) (Fig. 9). This mapping revealed that there is high evidence for relevant shares of land across the EU potentially available for industrial crop cultivation.

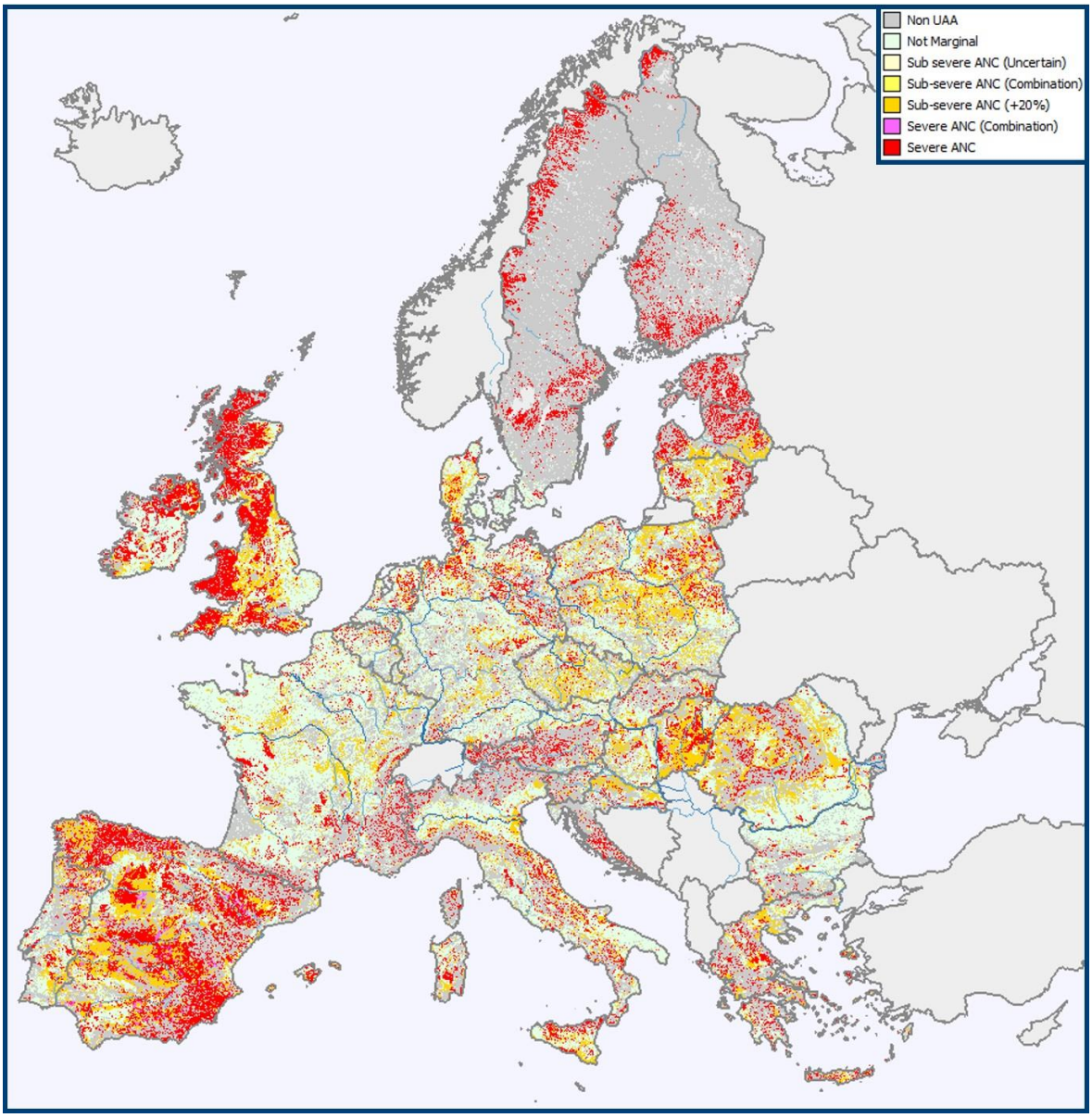

Figure 9: Marginal lands based on biophysical constraints in EU-28 (marginal lands are in the severe and sub-severe class) taken from Elbersen et al. (2018b).

In total, app. 647,000 km² of AEZ 1-3 were identified to be marginal land (Fig. 10, Table 15) corresponding to an area larger than France (640,679 km²). The marginal areas in AEZ 1, AEZ 2 and AEZ 3 are in a similar surface range (Fig. 10). Overall, the marginal surface

covers around 28% of total agricultural area[1] of the EU-28[2] (Table 15). This marginal land is expected to be partly available for industrial crop cultivation. However, current uses of these marginal lands still need to be analyzed further as the aim of MAGIC is to identify a land resource that can be used for industrial crops without competing with food production and threatening food security.

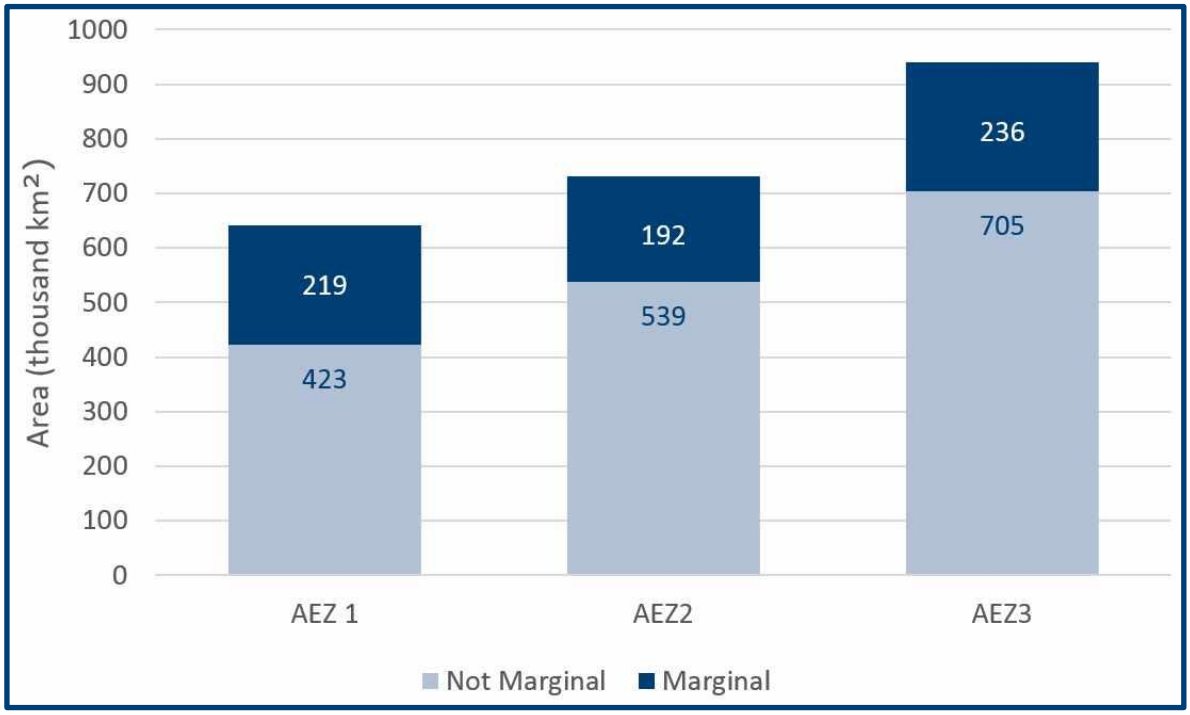

Figure 10: Area of marginal land per agro-ecological zone (AEZ).

Within this marginal land, 44 constraint categories (single constraints or constraint combinations) were identified, with total areas per constraint ranging from 1 to 155,519 km² (Tables 15, A2). Nearly all constraint categories can be found within each AEZ, whereas the relevancies of the constraint categories (i.e. their shares of total marginal land per AEZ) strongly differ in many cases (Table 15). In total, 112 MAEZ (the combination of a constraint or a constraint combination and an AEZ) were identified (Table 15). A closer look at the distributions of the constraints revealed that the prevalent MAEZ are rather scattered than connected areas (Figs. 11-16). This explains why there are multiple best-practice solutions per MAEZ because the site-specific conditions are strongly differing within each MAEZ.

[1] The mapping of the first version of MAEZ in MAGIC presented here is limited to a so-called 'agricultural mask'. This mask includes all land that was classified in an agricultural land cover class in at least one of the four Corine Land Cover (CLC) versions developed in time: CLC 1990, CLC 2000, CLC 2006, CLC 2012. So the classification in this land cover class makes it 'agricultural', but this does not mean that there is proven agricultural use of this land at all, let alone in a continuous period between 1990-2012.
[2] The current MAEZ has been developed for EU-28. However, it is planned to also map in a similar way the marginal lands in Ukraine. This information is however not available yet.

Table 15: Results from Task 2.1: Areas of both the 112 identified MAEZ and the land categories. The total areas per constraint category are also given (across AEZ 1-3). All values were colorized by size of area per category. Abbreviations: CH = Salinity or other contaminations; CL = Low temperature, high temperature or dryness; FE = Acidity, alkalinity or soil organic matter; RT = Shallow rooting depth or unfavourable texture; TR = Steep slope; WT = Limited soil drainage or excess soil moisture.

	Area of MAEZ (km²)			
Constraint / land category	AEZ 1	AEZ 2	AEZ 3	Total area of constraint / land category across AEZ 1-3 (km²)
RT	62,247	51,823	41,449	155,519
CL	27,752	4,564	79,780	112,096
WT	2,526	65,322	40,233	108,081
TR	31,332	5,710	11,362	48,404
RT - TR	15,636	14,656	2,157	32,449
CL -RT	25,675	593	6,064	32,332
CL - WT	701	13,141	16,263	30,105
FE	15,205	3,087	5,246	23,538
CH	6,883	3,642	11,987	22,512
CL -FE	14,527	291	3,524	18,342
WT -RT	348	10,541	1,745	12,634
CL -TR	2,920	1,577	4,189	8,686
CL -RT - TR	4,240	1,072	1,150	6,462
CL - WT -RT	95	1,531	3,472	5,098
CL - WT -TR	12	4,663	61	4,736
CL -FE -RT	4,272	47	97	4,416
CL -FE -RT - TR	4,272	47	97	4,416
CL - WT -RT - TR	603	2,361	1,421	4,385
CL -FE -TR	151	2,361	1,421	3,933
WT -TR	51	1,935	976	2,962
FE -RT	1,268	603	289	2,160
CL - WT - FE	0	1,344	594	1,938
WT -RT - TR	4	1,158	58	1,220
WT - FE	11	986	198	1,195
CL -CH	1,173	0	0	1,173
FE - CH	200	1	950	1,151
CH -TR	273	46	654	973
CL - WT - FE -RT	0	185	697	882
CH - RT	280	107	195	582
WT -CH	37	239	154	430
CL - WT - FE -TR	0	417	1	418
CL - WT - FE -RT - TR	1	143	106	250
CL -FE - CH	244	0	0	244
FE -TR	117	49	51	217
WT - FE -RT	0	87	10	97
WT - FE -TR	0	77	1	78
CL -CH - RT	54	0	0	54
FE -RT - TR	7	32	6	45
CH - RT - TR	26	2	16	44
CL -CH -TR	18	0	0	18
FE - CH -TR	1	0	17	18
FE - CH - RT	4	0	7	11
CL - WT -CH	5	0	0	5
WT - FE - CH	0	0	1	1
Total marginal	218,962	192,302	235,569	646,833
Total not marginal	422,565	538,855	704,818	1,666,238
Total	641,527	731,157	940,387	2,313,071

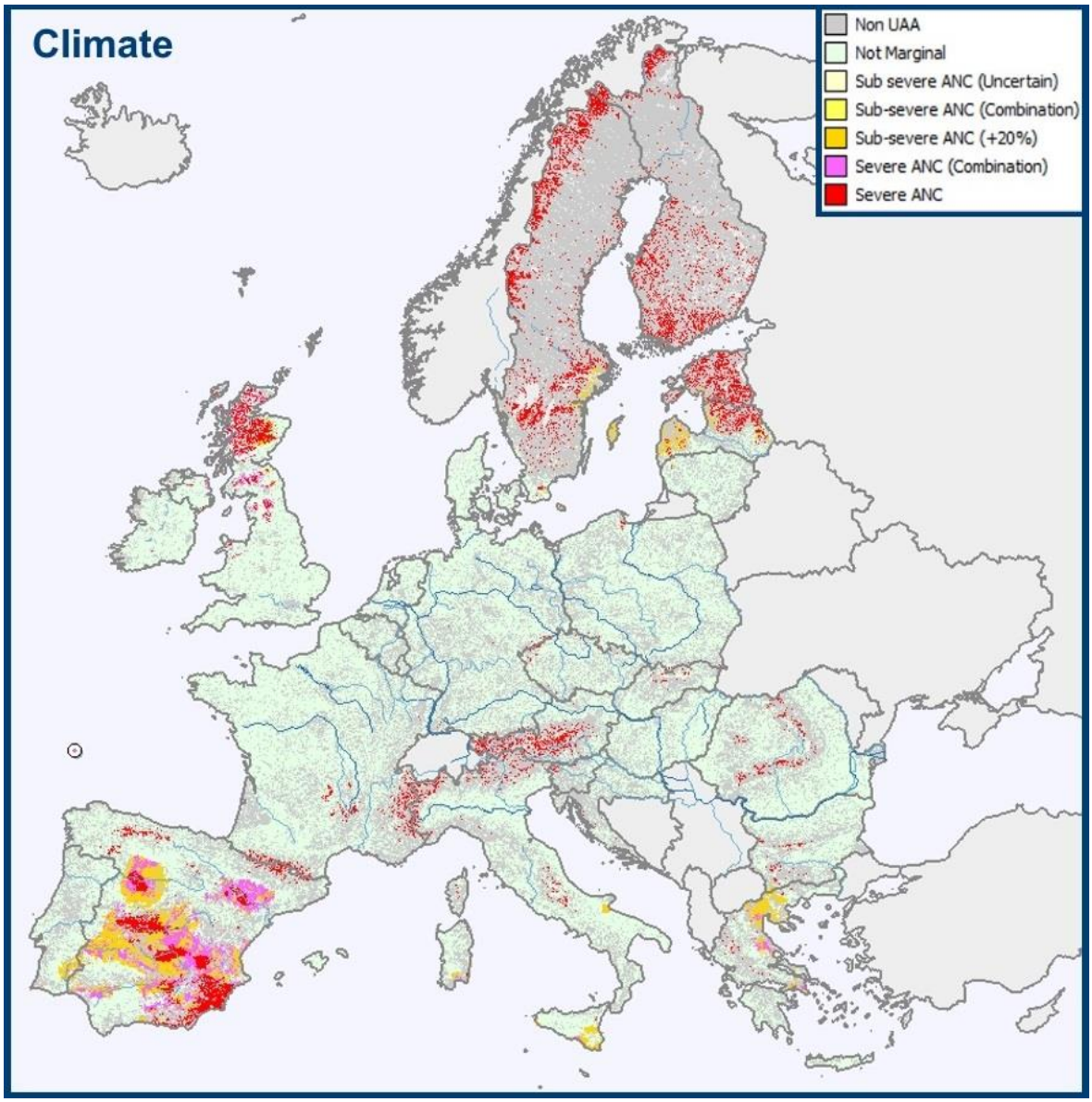

Figure 11: Spatial distribution of adverse climate (low temperature and/or dryness) across Europe (EU-28) (adapted from Elbersen et al., 2018b).

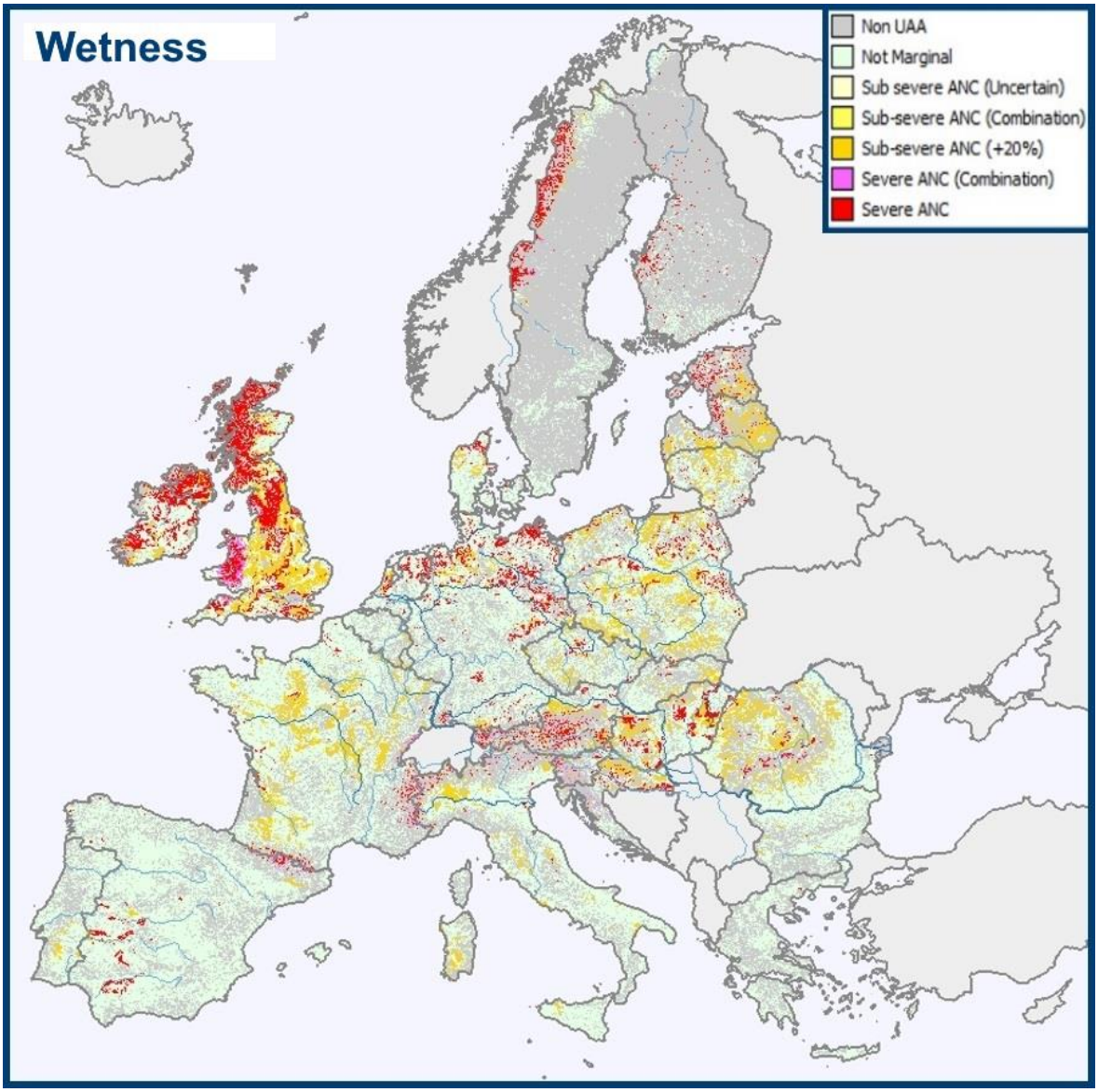

Figure 12: Spatial distribution of excess soil wetness (excess soil moisture and/or poor soil drainage) across Europe (EU-28) (adapted from Elbersen et al., 2018b).

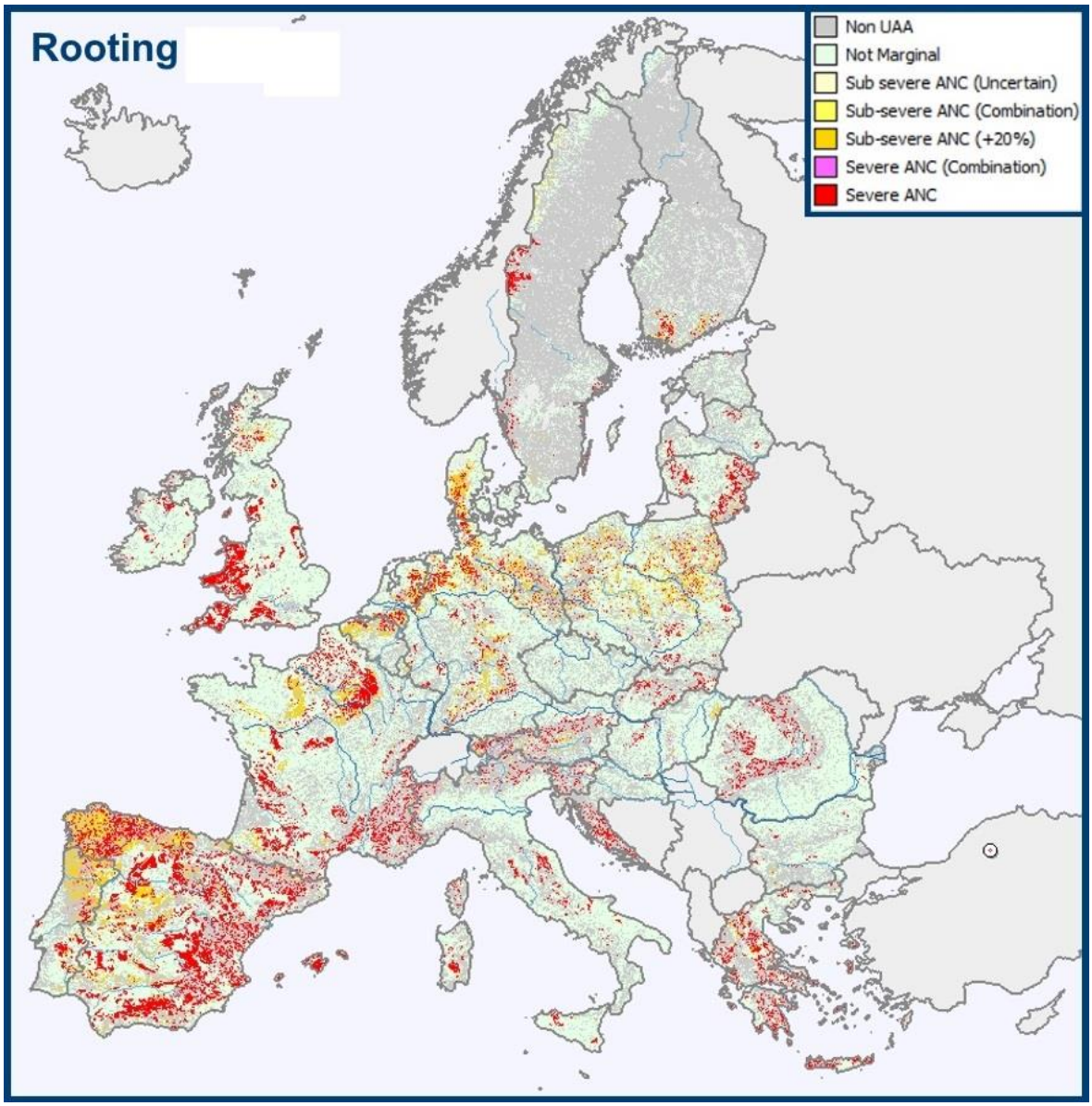

Figure 13: Spatial distribution of adverse rooting conditions (unfavourable texture and/or stoniness and/or shallow rooting depth) across Europe (EU-28) (adapted from Elbersen et al., 2018b).

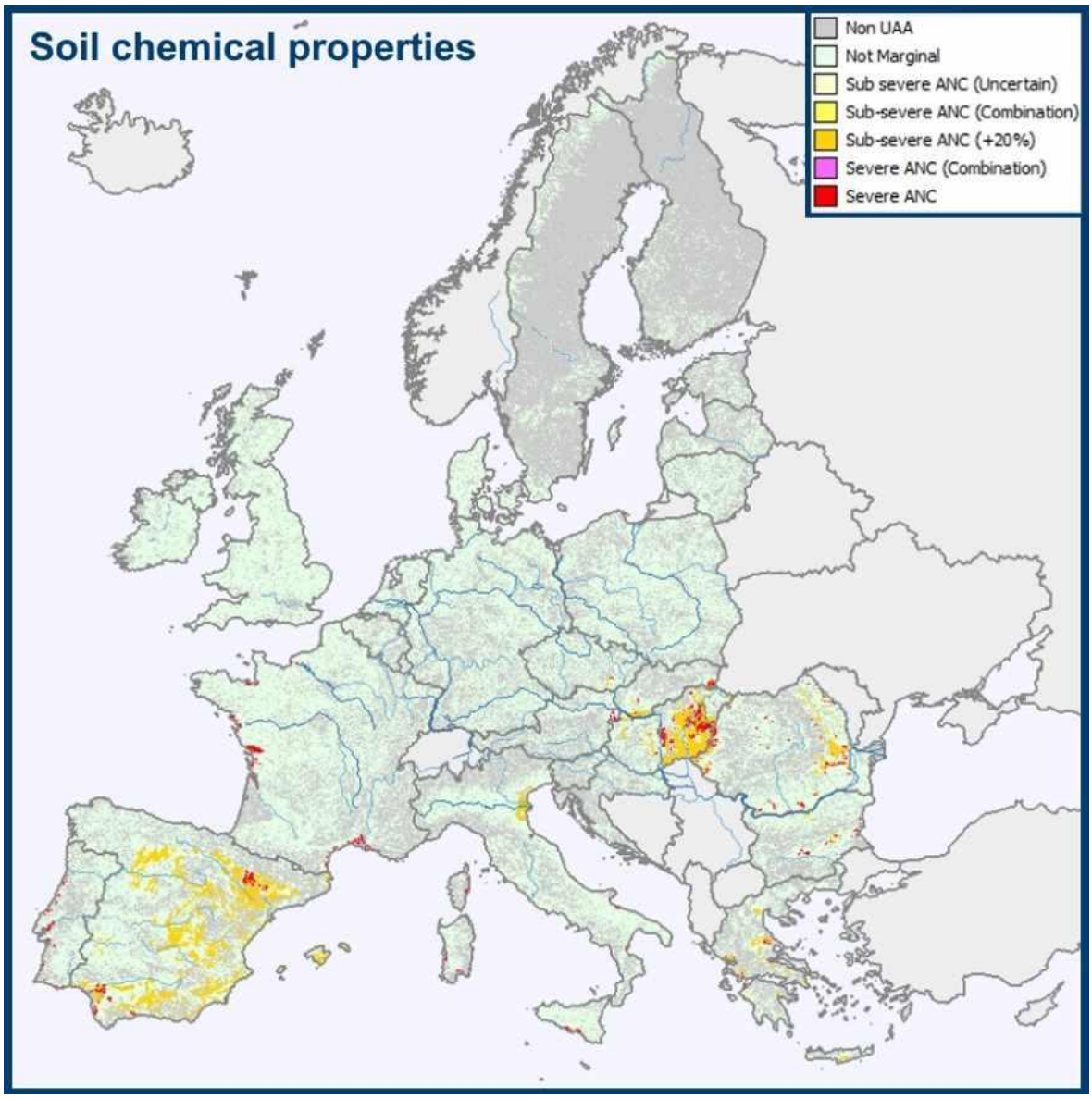

Figure 14: Spatial distribution of adverse soil chemical properties across Europe (EU-28) (adapted from Elbersen et al., 2018b).

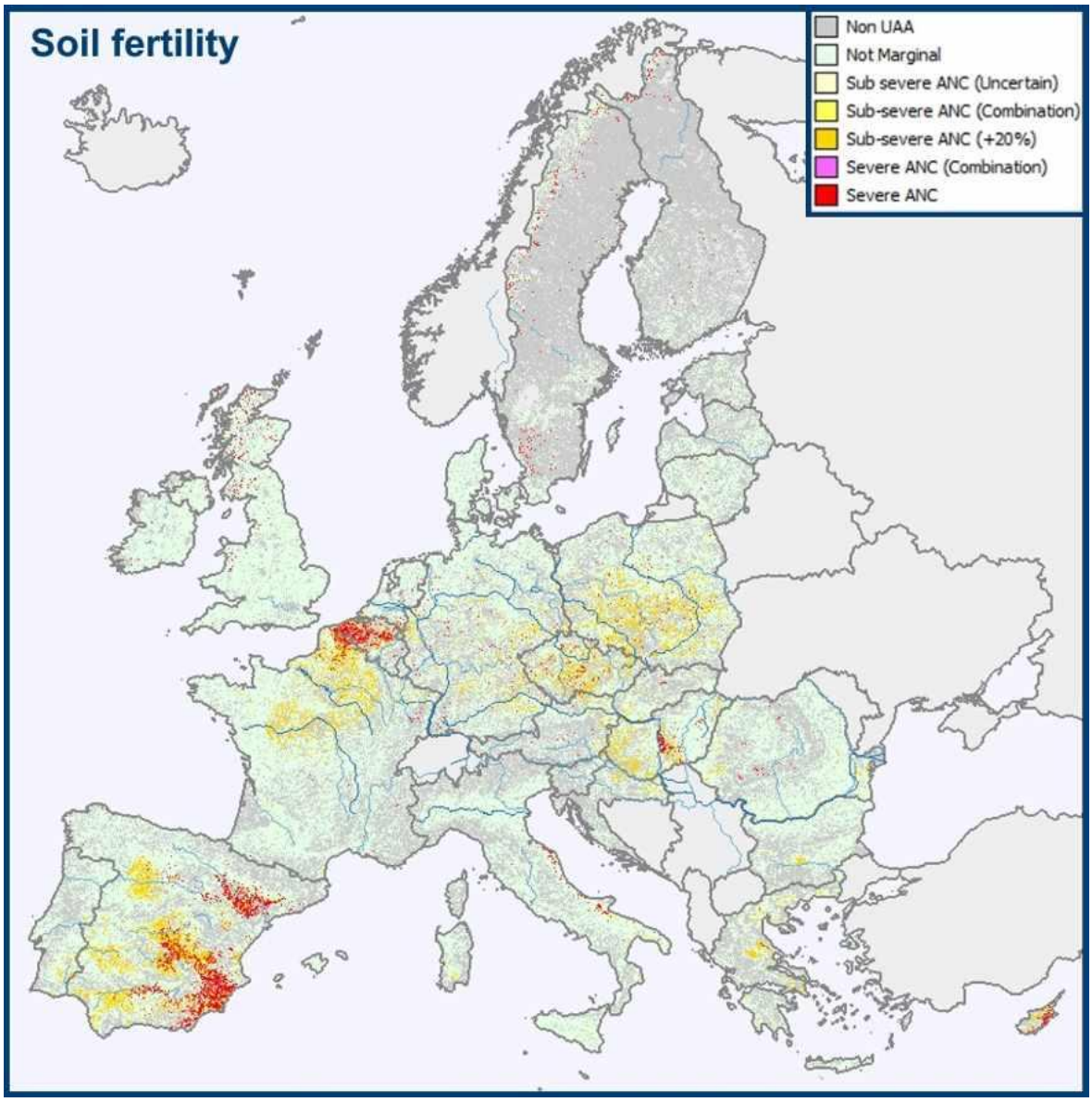

Figure 15: Spatial distribution of adverse soil fertility across Europe (EU-28) (adapted from Elbersen et al., 2018b).

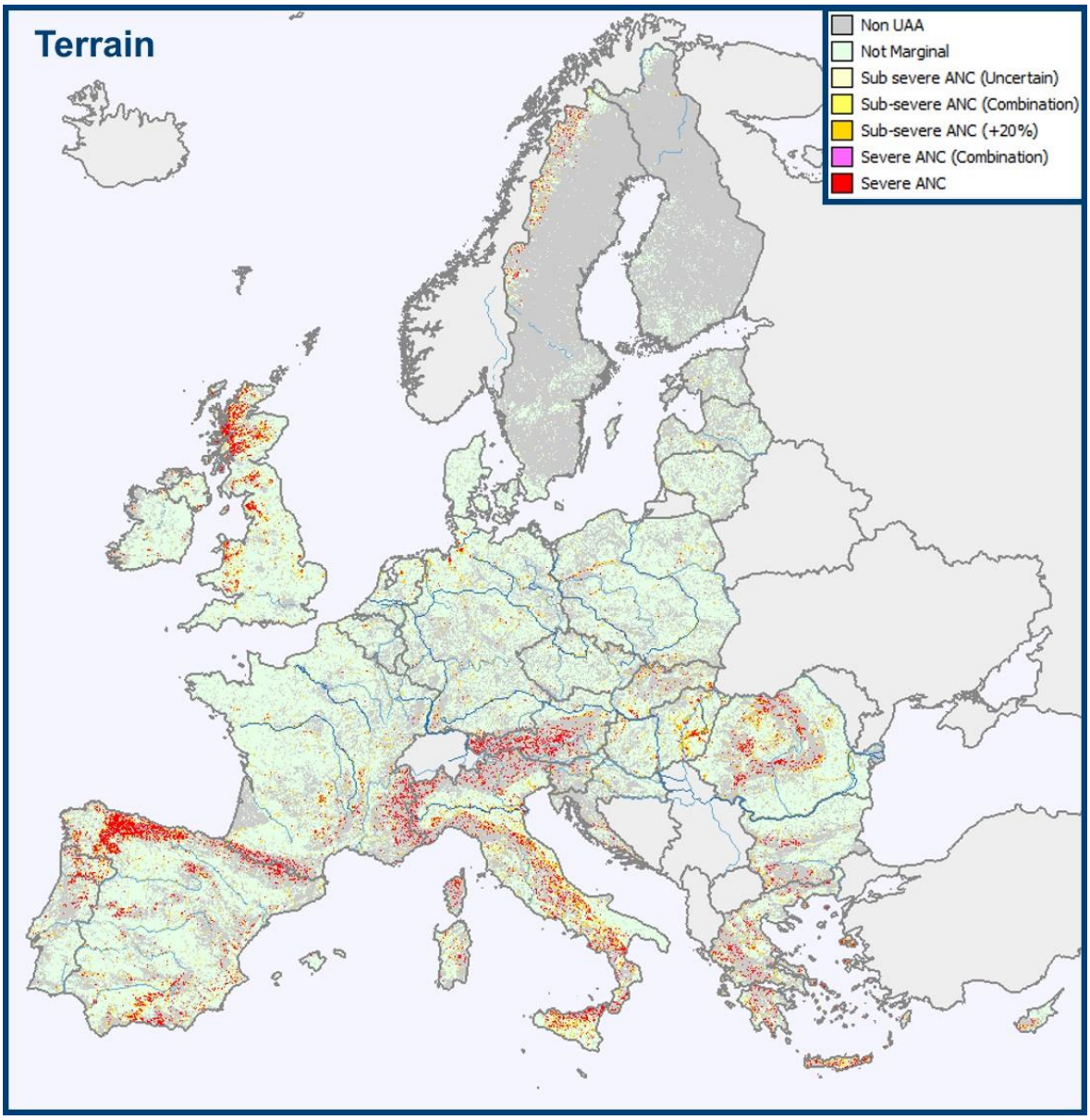

Figure 16: Spatial distribution of adverse terrain across Europe (EU-28) (adapted from Elbersen et al., 2018b).

However, a comparison of the shares of total marginal land per AEZ of the constraints showed that some MAEZ are more prevalent than others and that there are relevant differences between the AEZ. For example, shallow rooting depth (RT) is the predominant single biophysical constraint across all AEZ with about 155,519 km² in total (Table 15). Other important constraints are climate limitations due of either short growing season or dryness occurs as a single limitation on 112,096 km² and wetness because of 'Limited soil drainage leading to excess soil moisture' (WT) with 108,081 km². Climate – rooting combinations occur in 32,332 km² and steep slope is more significant with 48,404 km². (Table 15). While RT is among the top two MAEZ within each AEZ, other important constraints such as wetness (WT) are only relevant in two AEZ, accompanied by many MAEZ with low relevance (Table 16).

Table 16: Overview of marginal agro-ecological zones (MAEZ) with a share of total marginal area of the respective AEZ of ≥ 1%. Absolute area (km²) and relative share of total marginal area of AEZ of MAEZ (%) are given and colorized separately for each parameter and AEZ.

Mediterranean (AEZ 1)			Atlantic (AEZ 2)			Continental (AEZ 3)		
MAEZ[a]	km²	%[b]	MAEZ	km²	%	MAEZ	km²	%
RT_1	62,247	28%	WT_2	65,322	34%	CL_3	79,780	34%
TR_1	31,332	14%	RT_2	51,823	27%	RT_3	41,449	18%
CL_RT_1	27,752	13%	RT_TR_2	14,656	8%	WT_3	40,233	17%
CL_RT_1	25,675	12%	CL_WT_2	13,141	7%	CL_WT_3	16,263	7%
RT_TR_1	15,636	7%	WT_RT_2	10,541	5%	CH_3	11,987	5%
FE_1	15,205	7%	TR_2	5,710	3%	CL_RT_3	6,064	3%
CL_FE_1	14,527	7%	CL_WT_ TR_2	4,663	2%	FE_3	5,246	2%
CH_1	6,883	3%	CL_2	4,564	2%	CL_TR_3	4,189	2%
CL_FE_RT_1	4,272	2%	CH_2	3,642	2%	CL_FE_3	3,524	1%
CL_RT_TR_1	4,240	2%	FE_2	3,087	2%	CL_WT_RT_TR_3	3,472	1%
CL– TR_1	2,920	1%	CL_WT_RT_TR_2	2,361	1%	RT_TR_3	2,157	1%
WT_1	2,526	1%	CL_FE_TR_2	2,361	1%	WT_RT _3	1,745	1%
FE_RT_1	1,268	1%	WT_TR_2	1,935	1%	CL_WT_RT_TR_3	1,421	1%
CL_CH_1	1,173	1%	CL_TR_2	1,577	1%	CL_FE_TR_3	1,421	1%
			CL_WT_RT_2	1,531	1%			
TOTAL	215,656	99%	TOTAL	186,914	98%	TOTAL	218,915	93%

[a] MAEZ with less than 1% of total marginal area were excluded from table. Abbreviations denote as follows: CH = Salinity or other contaminations; CL = Low temperature, high temperature or dryness; FE = Acidity, alkalinity or soil organic matter; RT = Shallow rooting depth or unfavourable texture; TR = Steep slope; WT = Limited soil drainage or excess soil moisture. The numbers behind the constraints denotes for the respective AEZ of each MAEZ (for example: RT_2 = adverse rooting conditions in AEZ 2).

[b] Percentage of total marginal area per AEZ (excluding constraints with less than 1%); values were rounded up.

The sum of all MAEZ with ≥ 1% of total marginal area per AEZ accounts for 93-99% of total marginal area across AEZ 1-3 in EU-28 (Table 15). Furthermore, the relevance of each single constraint (CH, CL, etc.) is even higher than (partly) shown in Table 15 when all MAEZ which include the respective constraint are considered and summed up (Tables 16 and 17, Fig. 17): Across Europe (EU-28), an area larger than the United Kingdom is affected by adverse rooting conditions or combinations of adverse rooting with other limitations (262,118 km²) and an area larger than Romania is affected by climatic limitations either occurring as a single limitation or in combination (239,989 km²).

Table 17: Total area of MAEZ which include at least one of the respective major constraints, i.e. also constraint combinations were considered. Values are colorized per category.

	Total area (km²) of all MAEZ including the respective major constraint[a]					
Region[b]	Chemical	Climate	Fertility	Rooting	Terrain	Wetness
AEZ 1	9,198	82,506	36,071	114,823	55,455	4,394
AEZ 2	4,037	32,199	7,619	85,019	34,168	104,130
AEZ 3	13,981	117,807	12,183	59,066	22,614	65,991
AEZ 1-3	27,216	232,512	55,873	258,908	112,237	174,515

[a] Chemical = Salinity or other contaminations; Climate = Low temperature or dryness; Fertility = Acidity, alkalinity or low soil organic matter; Rooting = Shallow rooting depth or unfavourable texture; Terrain = Steep slope; Wetness = Limited soil drainage or excess soil moisture.
[b] AEZ = Agro-ecological zone.

Table 18: Total share of agricultural land covered by all MAEZ which include at least one of the respective major constraints, i.e. also constraint combinations were considered. Values are colorized per category.

	Total area of all MAEZ including the respective major constraint[a] (% of agricultural land[b])					
Region[c]	Chemical	Climate	Fertility	Rooting	Terrain	Wetness
AEZ 1	1%	13%	6%	18%	9%	1%
AEZ 2	1%	4%	1%	12%	5%	14%
AEZ 3	1%	13%	1%	6%	2%	7%
AEZ 1-3	**1%**	**10%**	**2%**	**11%**	**5%**	**8%**

[a] Chemical = Salinity or other contaminations; Climate = Low temperature or dryness; Fertility = Acidity, alkalinity or low soil organic matter; Rooting = Shallow rooting depth or unfavourable texture; Terrain = Steep slope; Wetness = Limited soil drainage or excess soil moisture.
[b] The area share is calculated as share of land that can be categorized as agricultural land cover class since 1990 (according to Corine landcover 1990-2012).
[c] AEZ = Agro-ecological zone.

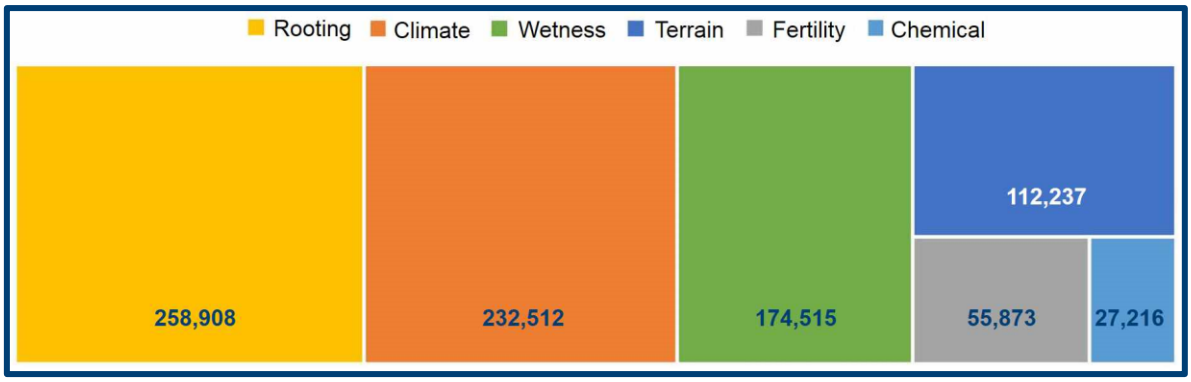

Figure 17: Overview of marginal area (km²) affected by the respective constraint. For each constraint, the areas of all MAEZ were merged which include the respective constraint. Abbreviations as follows: Chemical = Salinity or contaminations; Climate = Low temperature or dryness; Fertility = Acidity, alkalinity or low soil organic matter; Rooting = Shallow rooting depth or unfavourable texture; Terrain = Steep slope; Wetness = Limited soil drainage or excess soil moisture.

The most prevalent MAEZ are further described in Table 19 according to the dominant bio-physical constraints and additional risks. For example, areas with limiting rooting conditions (RT: shallow rooting depth, sand, heavy clay or peat) are MAEZ in AEZ 1, AEZ_2, and AEZ_3 thus denoted as 'RT_1' (for AEZ 1), 'RT_2' (for AEZ 2) and RT_3 (for AEZ 3) (Tables 16, 19). The additional risks include environmental threats such as the occurrence of desertification, erosion, soil compaction and waterlogging. These threats need to be addressed by planning appropriate crop management measures for MALLIS development, as further described in Chapter 4. The prevalent MAEZ are recommended to be considered for the selection of a site for new field trial establishment as far as there is not enough information available in literature.

Table 19: Most relevant (in terms of area) MAEZ (the combinations of AEZ and constraint) identified for different environmental zones in Europe (Table 16). Both the relevant potential additional risks per constraint through non-utilization and the overall chances of best practice low-input agricultural utilization are provided.

AEZ	Constraints (combinations) - MAEZ	Further description of constraints (combinations)	Additional risks	Overall chances through implementation of optimized MALLIS
Mediterranean (AEZ 1)	CL_1	Adverse climate - Dryness	Desertification/ salinization	• Avoid HNV[a] farmland loss (biodiversity),
	FE_1	Low soil fertility – low SOC[b]	Loss of SOC, erosion	• Increase biomass
	RT_1	Adverse rooting –shallow soils, stoniness, heavy clay	Erosion, compaction, waterlogging	• Stop land abandonment
	TR_1	Steep slope	Erosion	• Stop population decline
Atlantic (AEZ 2)	CL_2	Adverse climate – short growing season	-	• Alternative income opportunities
	RT_2, TX_2	Limitations rooting – soil texture (sandy soils, shallow & organic soils)	Loss SOC, erosion	
	WT_2	Excessive soil moisture	Loss SOC (peat)	
Continental (AEZ 3)	CH_3	Adverse chemical conditions - salinity & sodicity	Salinization, erosion	
	RT_3, TX_3	Limitations in rooting – organic & sandy soils	Erosion, loss SOC	
	WT_3	Excessive wetness	Loss SOC (peat)	

[a] HNV = High nature value
[b] SOC = Soil organic carbon

3.2.2. Climatic growth suitability of industrial crops across Europe

In this section, the spatial distribution of the overall growth suitability of the selected industrial crops across Europe (EU-28) is presented aiming to give a clear impression of both the overall climatic limitations of the industrial crops and the spatial distribution of their growth suitability. Therefore, the effects of climatic conditions on the crop-specific growth suitabilities of the selected industrial crops at both marginal and not marginal land will be illustrated (Tables 20-21, Figs. 19-37) based on the previously described suitability rankings for the respective climatic parameters (Sections 2.1. and 2.2.).

It was found, that the total area (on both marginal and not marginal land) of growth suitability per crop ranges from 220,512 km² (wild sugarcane) to 3,502,548 km² (tall wheatgrass) and that most crops are suitable for growing on larger areas in AEZ 1 (Ø 774,826 km²) compared to AEZ 2 (Ø 586,029 km²) and AEZ 3 (Ø 680,959 km²) (Table 20).

Table 20: Total area (km²) per selected industrial crop suitable for cultivation including both marginal and not marginal land across Europe (EU-28). All values are separately colorized per region.

Crop	AEZ 1	AEZ 2	AEZ 3	TOTAL (AEZ 1-3)
Biomass sorghum	923,294	326,140	89,387	1,338,821
Camelina	990,521	957,009	1,131,310	3,078,840
Cardoon	888,560	743,920	1,064,973	2,697,453
Castor	765,604	78,371	58,017	901,992
Crambe	1,000,114	942,298	1,315,944	3,258,356
Ethiopian mustard	886,852	545,926	140,467	1,573,245
Giant reed	593,625	14,935	22,796	631,356
Hemp	869,006	765,176	202,219	1,836,401
Lupin	938,804	344,861	411,090	1,694,755
Miscanthus	795,094	769,076	1,072,773	2,636,943
Pennycress	985,178	646,065	960,785	2,592,028
Poplar	391,410	895,043	1,236,671	2,523,124
Reed canary grass	388,910	838,947	1,410,215	2,638,072
Safflower	964,541	869,108	194,835	2,028,484
Siberian elm	865,477	310,539	407,419	1,583,435
Switchgrass	826,596	276,478	386,074	1,489,148
Tall wheatgrass	994,164	902,410	1,605,974	3,502,548
Wild sugarcane	219,722	790	0	220,512
Willow	434,215	907,456	1,227,262	2,568,933
Average	774,826	586,029	680,959	2,041,813

When focusing on marginal land, the selected industrial crops were also found to be better adapted to the growth conditions in AEZ 1 with an average growth suitability area of 153,747 km² compared to 82,771 km² in AEZ 2 and 68,356 km² in AEZ 3 (Table 21). The total area being completely unsuitable for the selected industrial crops accounts for 36,906 km² (or about 6% of total marginal land) across AEZ 1-3 whereas most of AEZ 1 and 2 are suitable for any of the crops (Fig. 18). This renders the importance of further research especially on northern conditions of the continental zone (AEZ 3). Conversely, the selection of industrial crops appears to be sufficient for AEZ 1 and 2.

Table 21: Total area (km²) per selected industrial crop suitable for cultivation on marginal land across Europe (EU-28) and share (%) of marginal land suitable for cultivation of crop. All values are separately colorized according to the respective parameters.

	AEZ 1		AEZ 2		AEZ 3		AEZ 1-3	
Crop	km²	%	km²	%	km²	%	km²	%
Biomass sorghum	193,118	88	31,322	16	6,323	3	230,763	36
Camelina	209,761	96	186,018	97	183,667	78	579,446	90
Cardoon	172,804	79	71,822	37	83,249	35	327,875	51
Castor	160,990	74	10,658	6	3,412	1	175,060	27
Crambe	216,577	99	175,244	91	130,959	56	522,780	86
Ethiopian mustard	184,988	84	43,177	22	10,111	4	238,276	37
Giant reed	129,501	59	2,459	1	1,173	0	133,133	21
Hemp	162,794	74	80,422	42	17,392	7	260,608	41
Lupin	201,888	92	36,790	19	37,162	16	275,840	43
Miscanthus	130,634	60	83,820	44	88,010	37	302,464	48
Pennycress	208,388	95	64,812	34	76,465	32	349,665	56
Poplar	48,166	22	159,938	83	150,428	64	358,532	60
Reed canary grass	45,863	21	124,828	65	147,470	63	318,161	53
Safflower	201,689	7	145,382	76	16,164	92	363,235	58
Siberian elm	179,148	82	20,611	11	28,261	12	228,020	36
Switchgrass	160,238	73	19,732	10	26,628	11	206,598	32
Tall wheatgrass	211,255	96	151,166	79	172,355	73	534,776	88
Wild sugarcane	46,516	21	252	0	0	0	46,768	7
Willow	56,880	26	164,191	85	119,536	51	340,607	56
Average	153,747	66	82,771	43	68,356	33	304,874	49

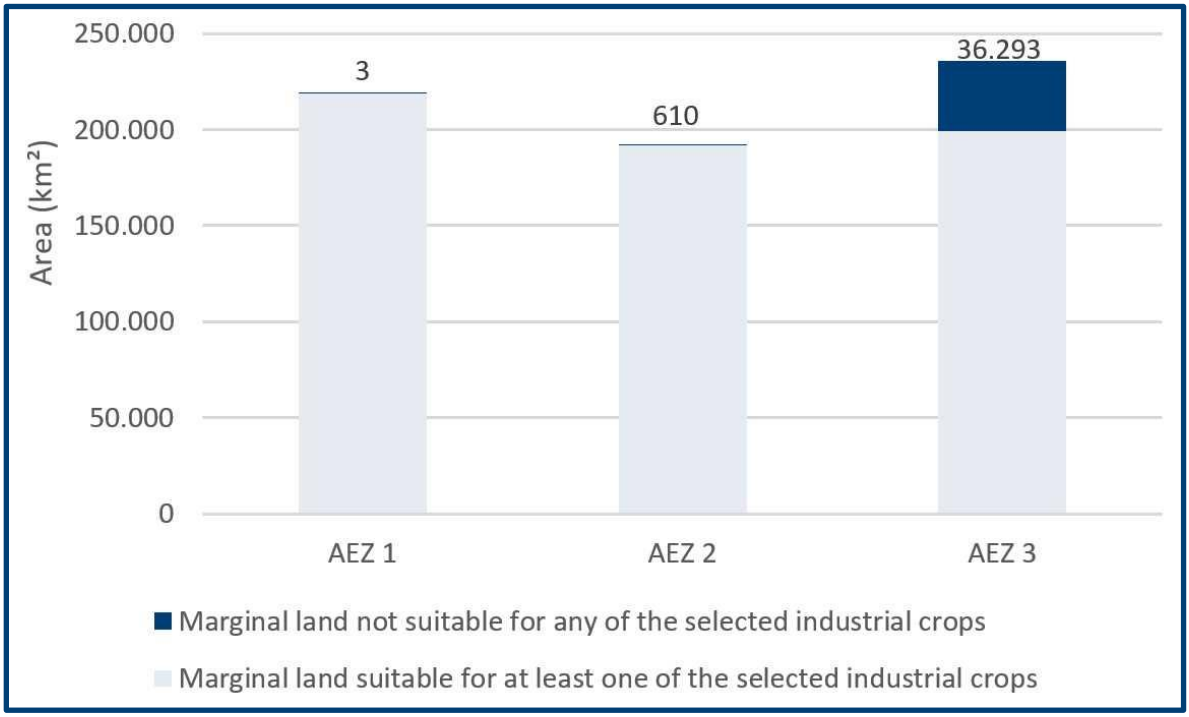

Figure 18: Marginal land not suitable for growing any of the selected industrial crops per AEZ (AEZ 1 = Mediterranean, AEZ 2 = Atlantic, AEZ 3 = Continental) within EU-28.

The following figures (Fig. 19-37) present the spatial distributions of the climatic growth suitabilities of the 19 pre-selected industrial crops (Table 1) in alphabetical order. Suitable areas for growing the selected crops are indicated in green color. Climatic factors limiting the crop growth are indicated for risk of frost killing (KF), too low growth degree days (GDD), too short length of growing season (LGS) and too low precipitation levels (RAIN).

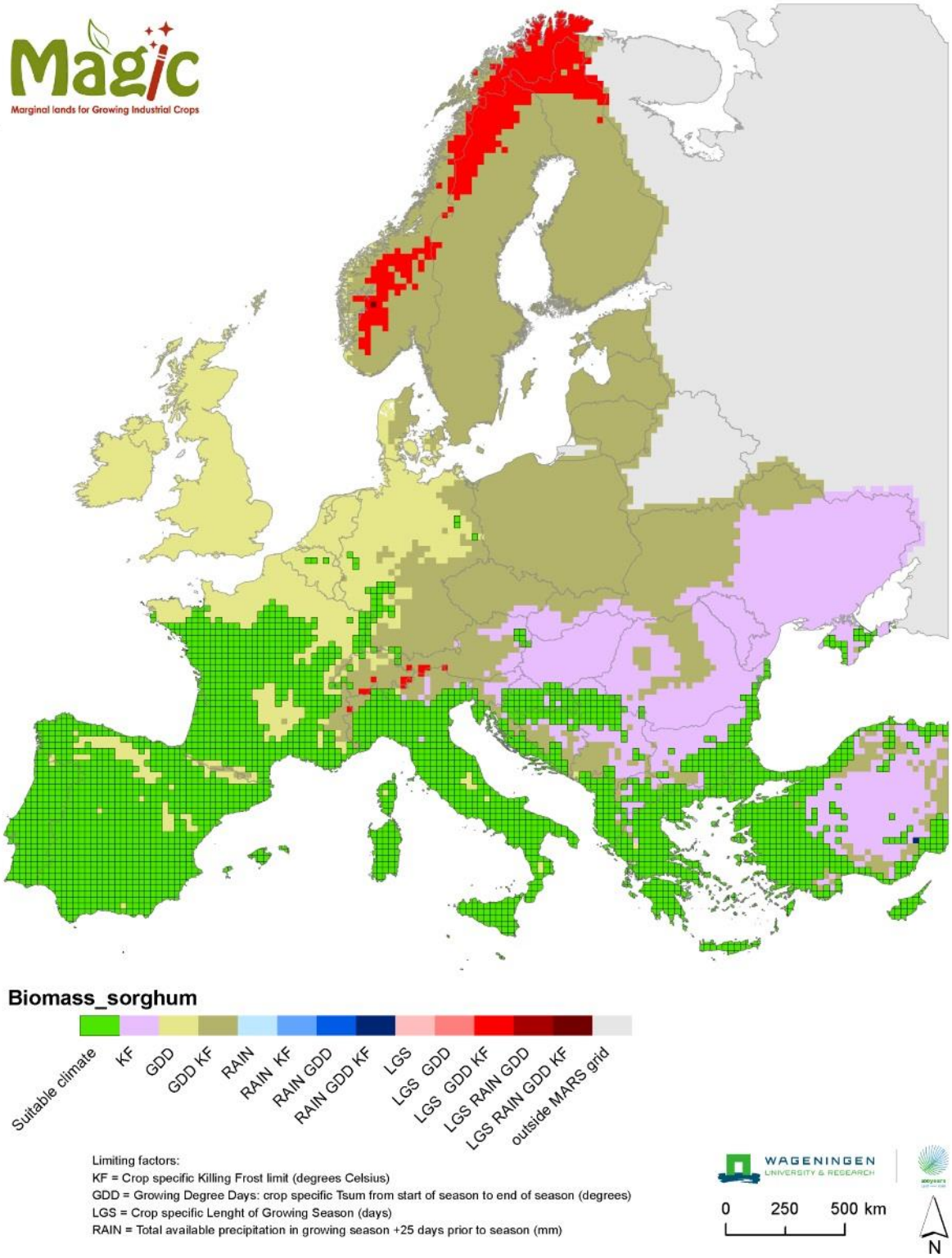

Figure 19: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for biomass sorghum based on climatic growth-suitability rankings presented in Chapter 2.

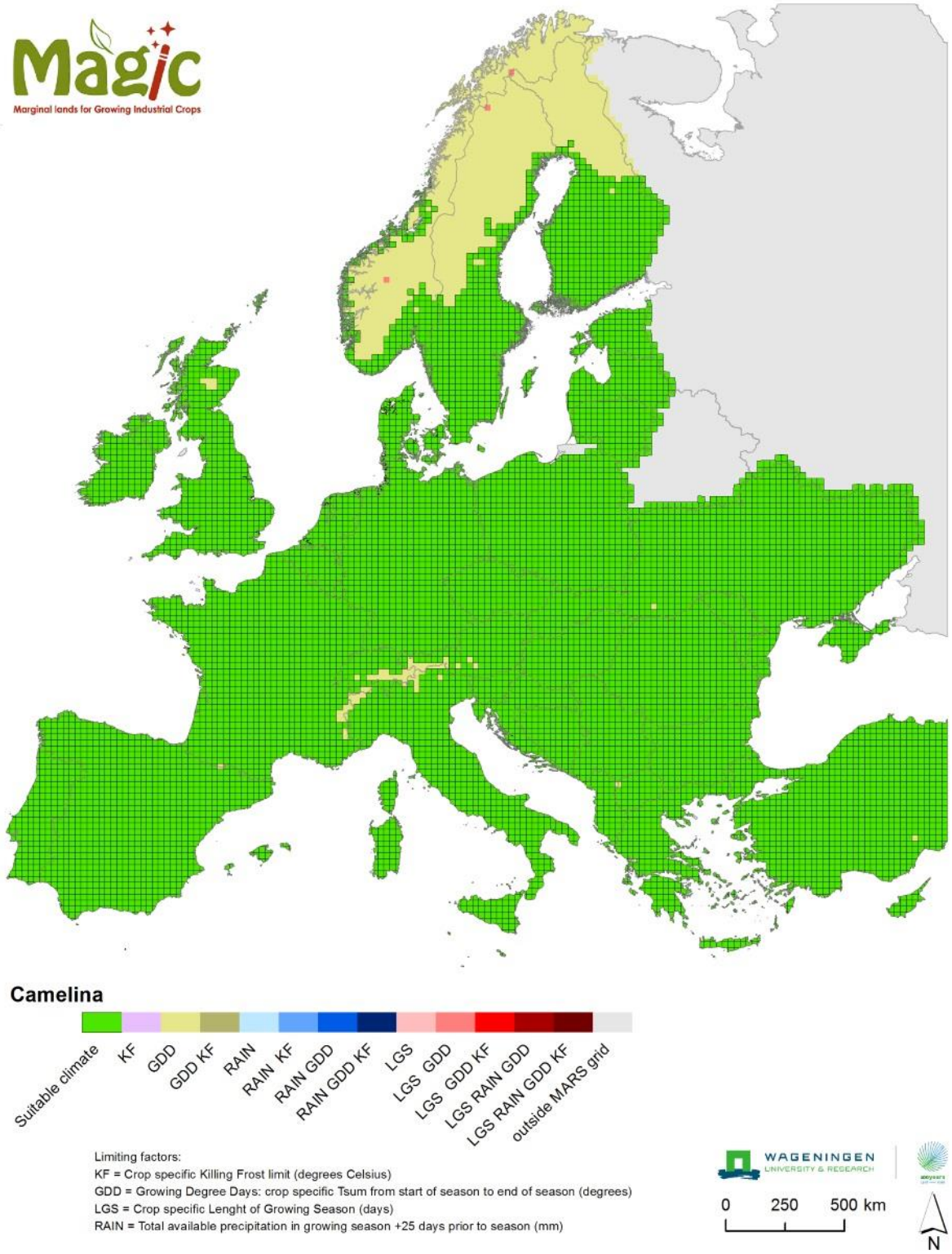

Figure 20: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for camelina based on climatic growth-suitability rankings presented in Chapter 2.

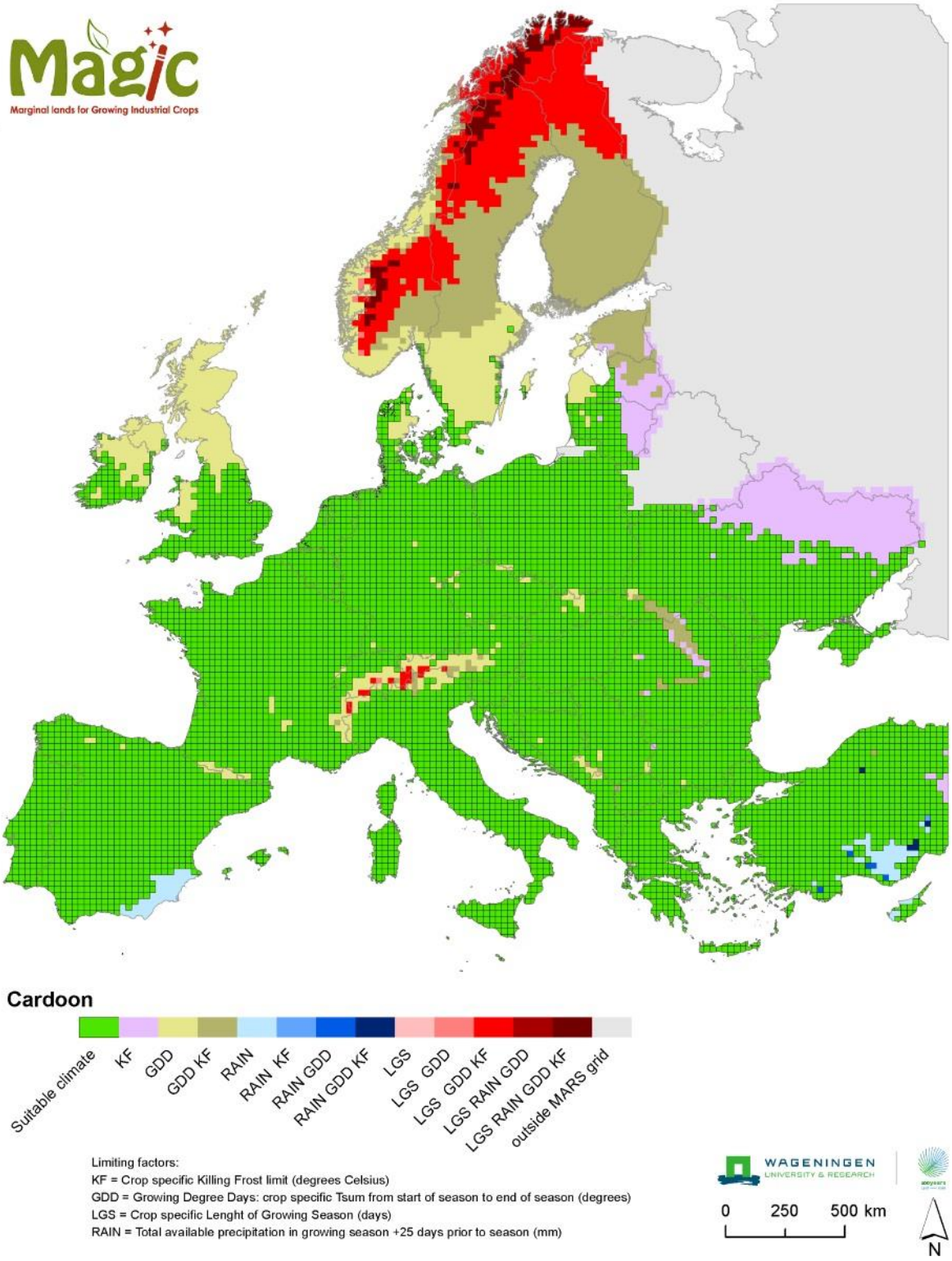

Figure 21: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for cardoon based on climatic growth-suitability rankings presented in Chapter 2.

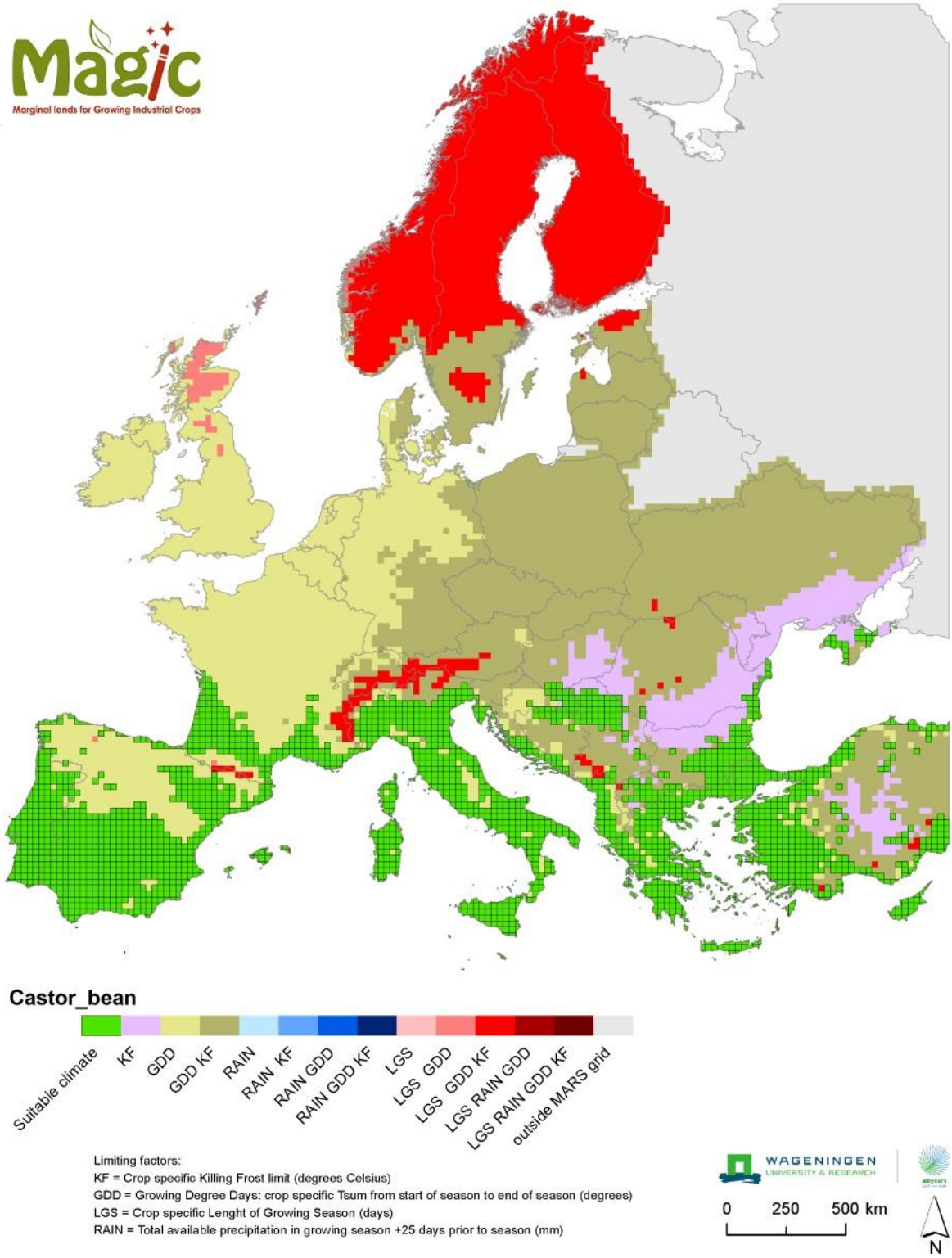

Figure 22: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for castor bean based on climatic growth-suitability rankings presented in Chapter 2.

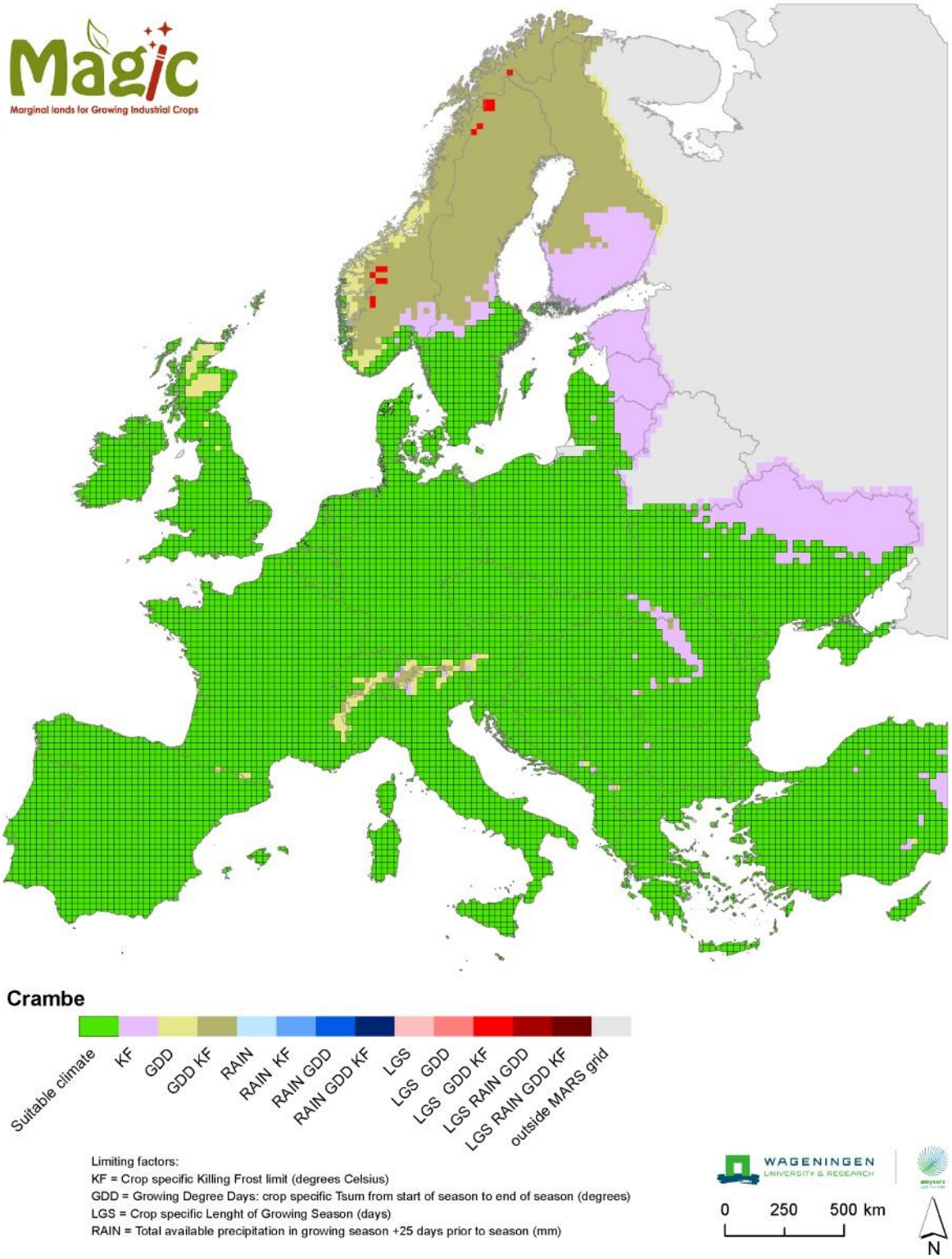

Figure 23: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for crambe based on climatic growth-suitability rankings presented in Chapter 2.

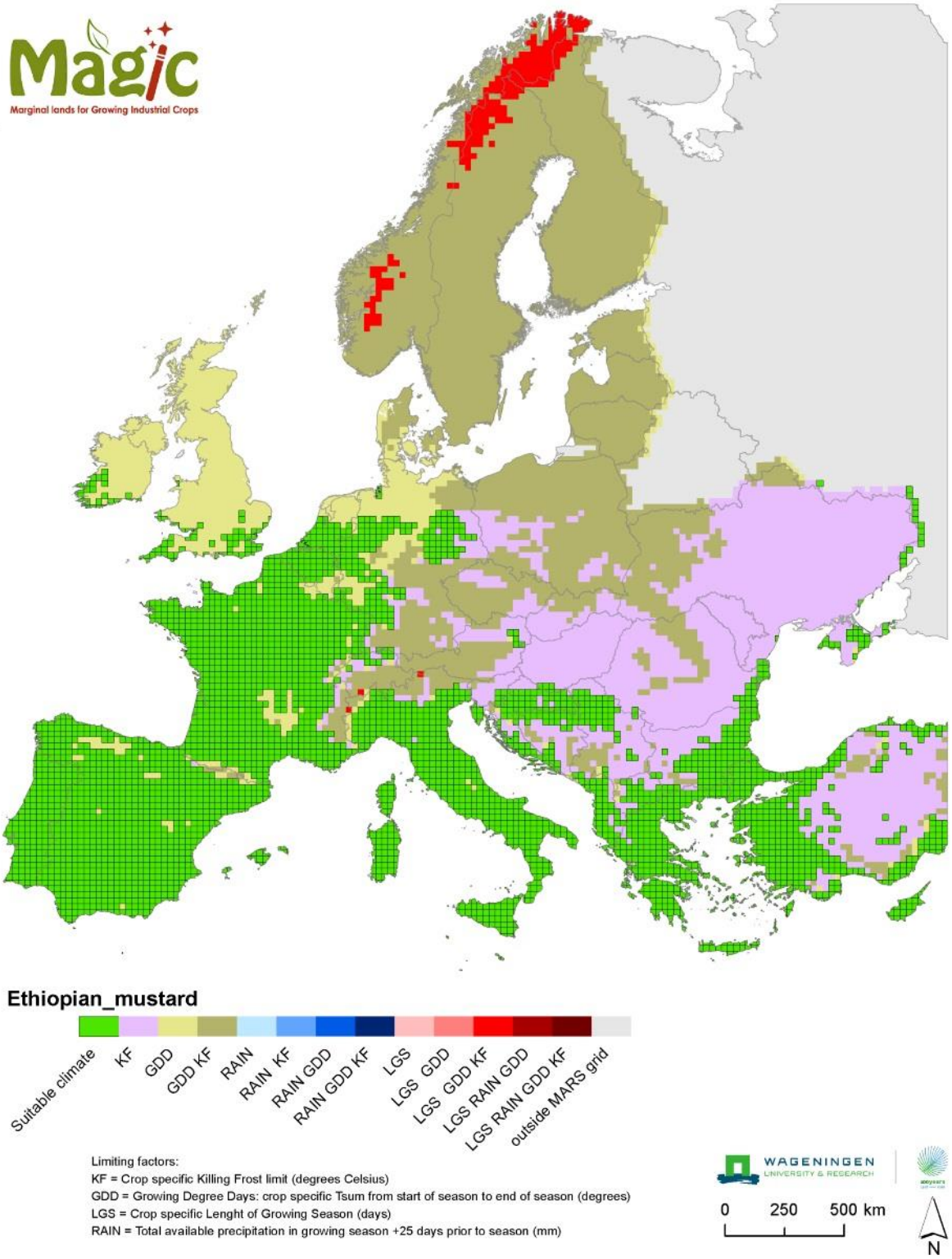

Figure 24: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for Ethiopian mustard based on climatic growth-suitability rankings presented in Chapter 2.

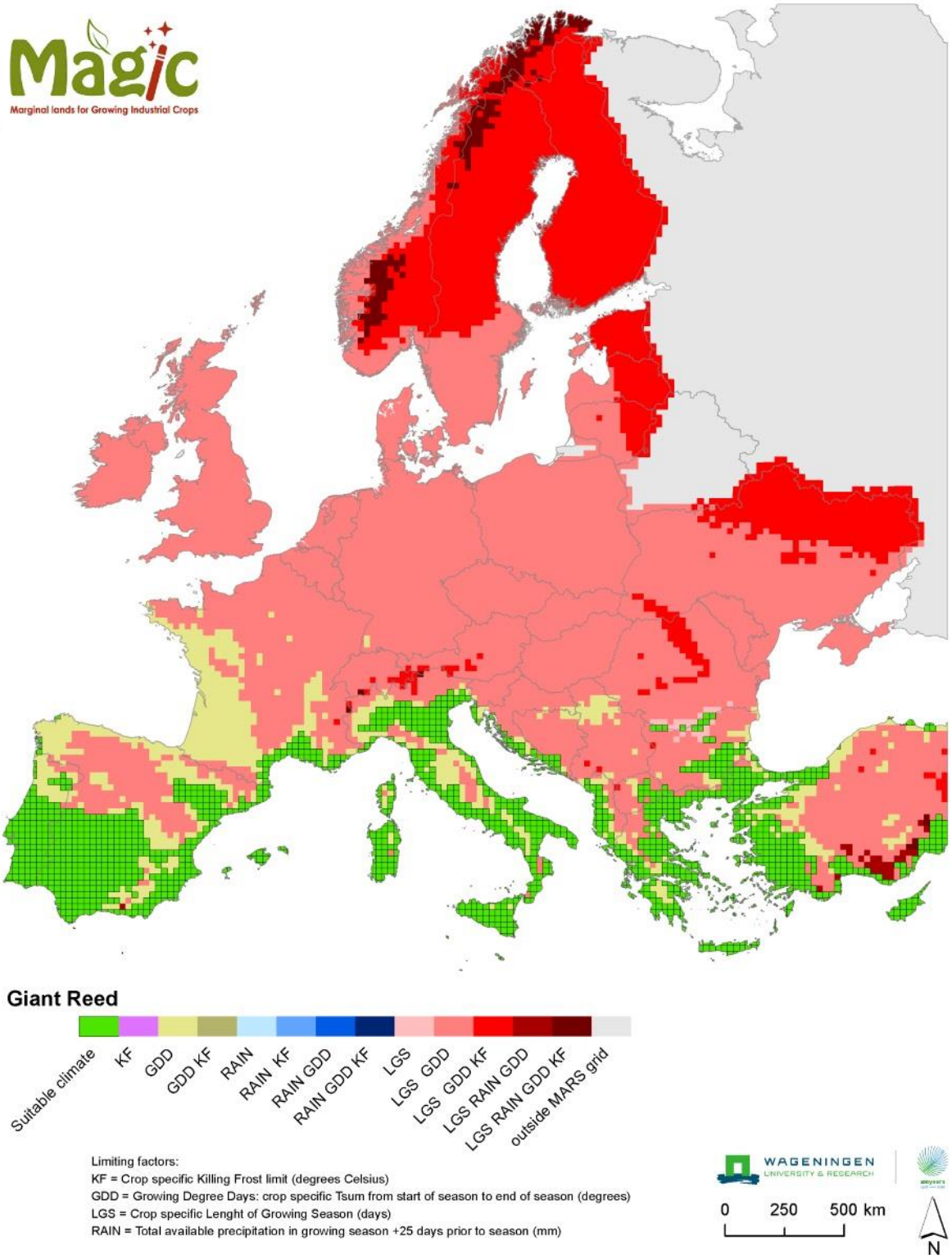

Figure 25: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for giant reed based on climatic growth-suitability rankings presented in Chapter 2.

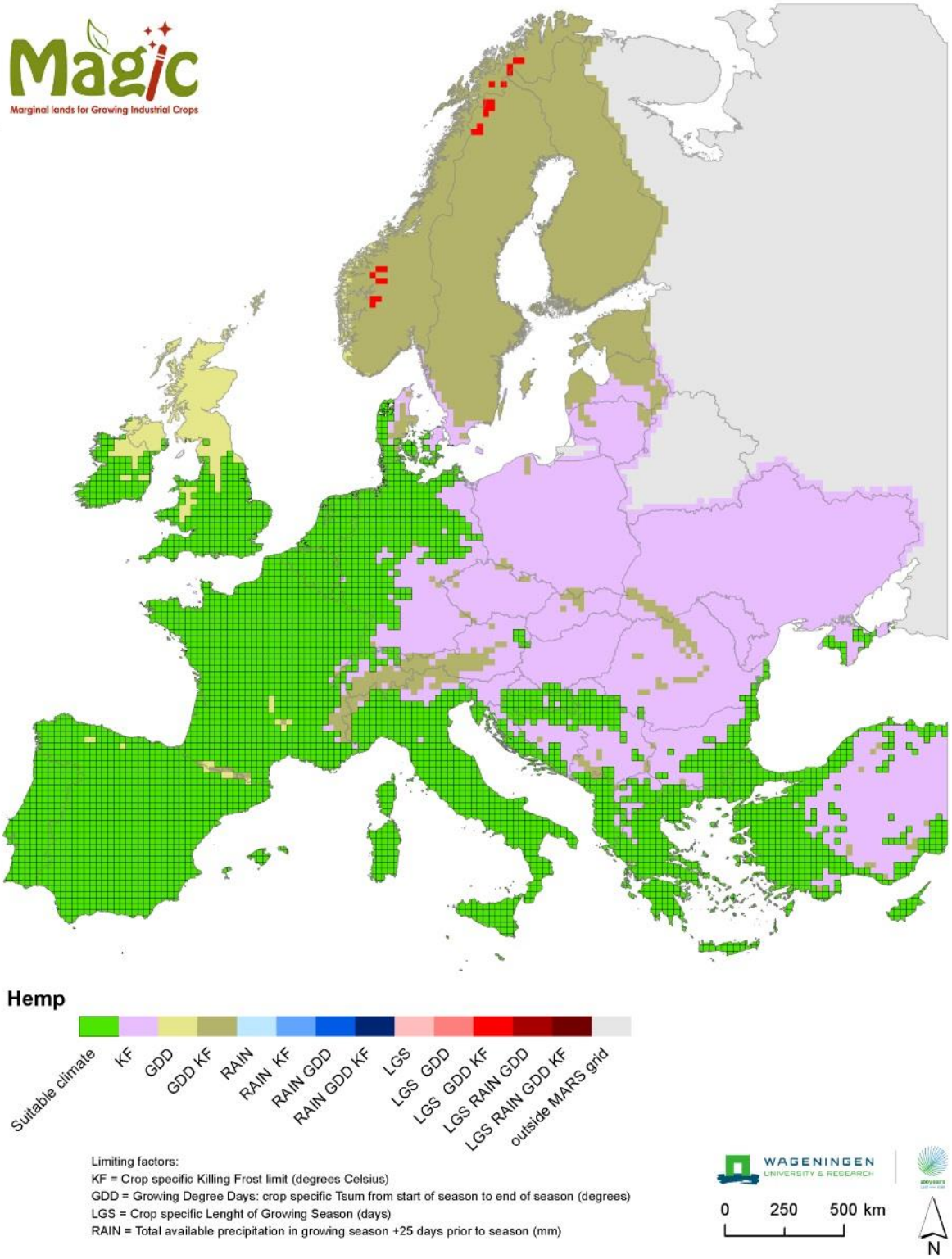

Figure 26: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for hemp based on climatic growth-suitability rankings presented in Chapter 2.

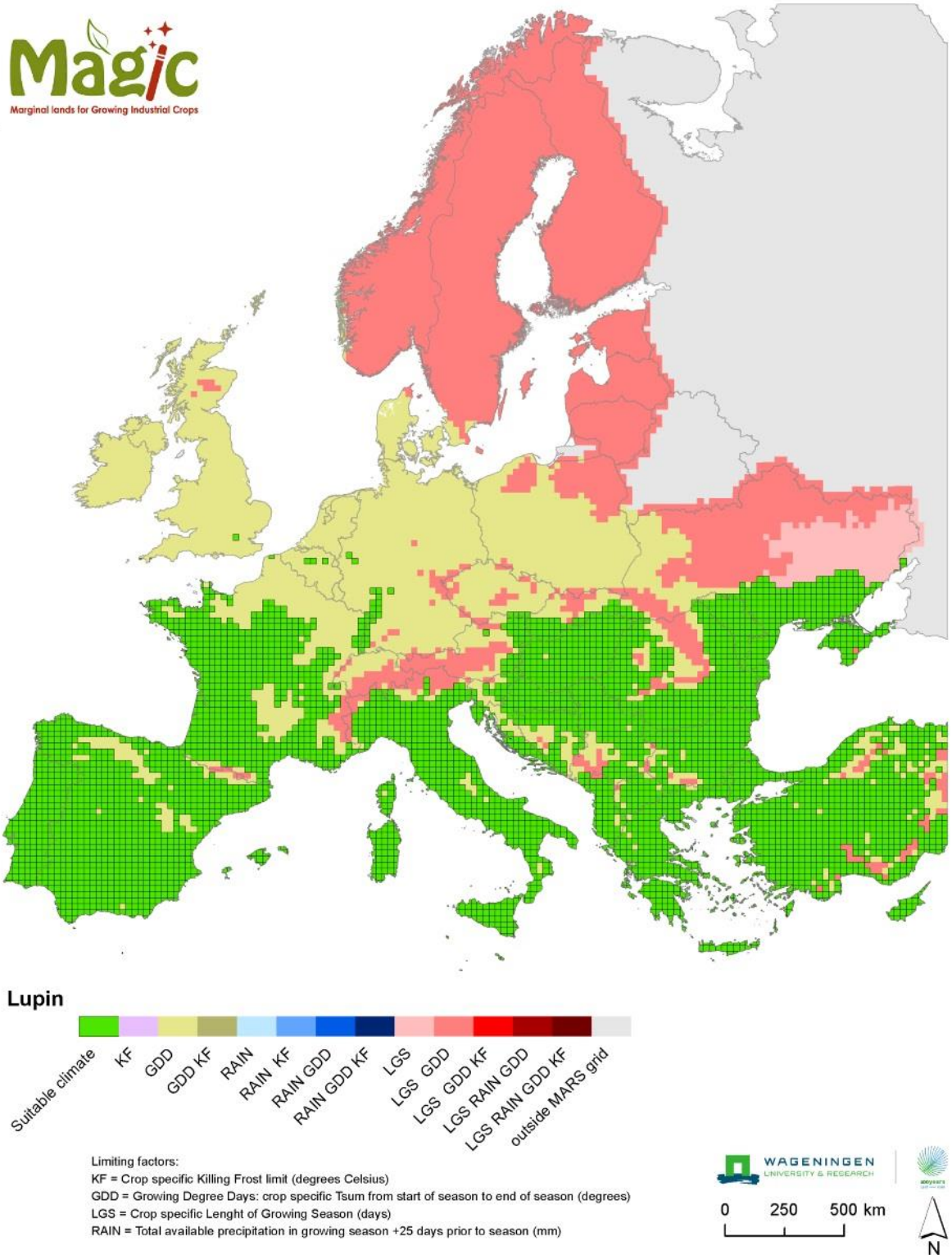

Figure 27: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for lupin based on climatic growth-suitability rankings presented in Chapter 2.

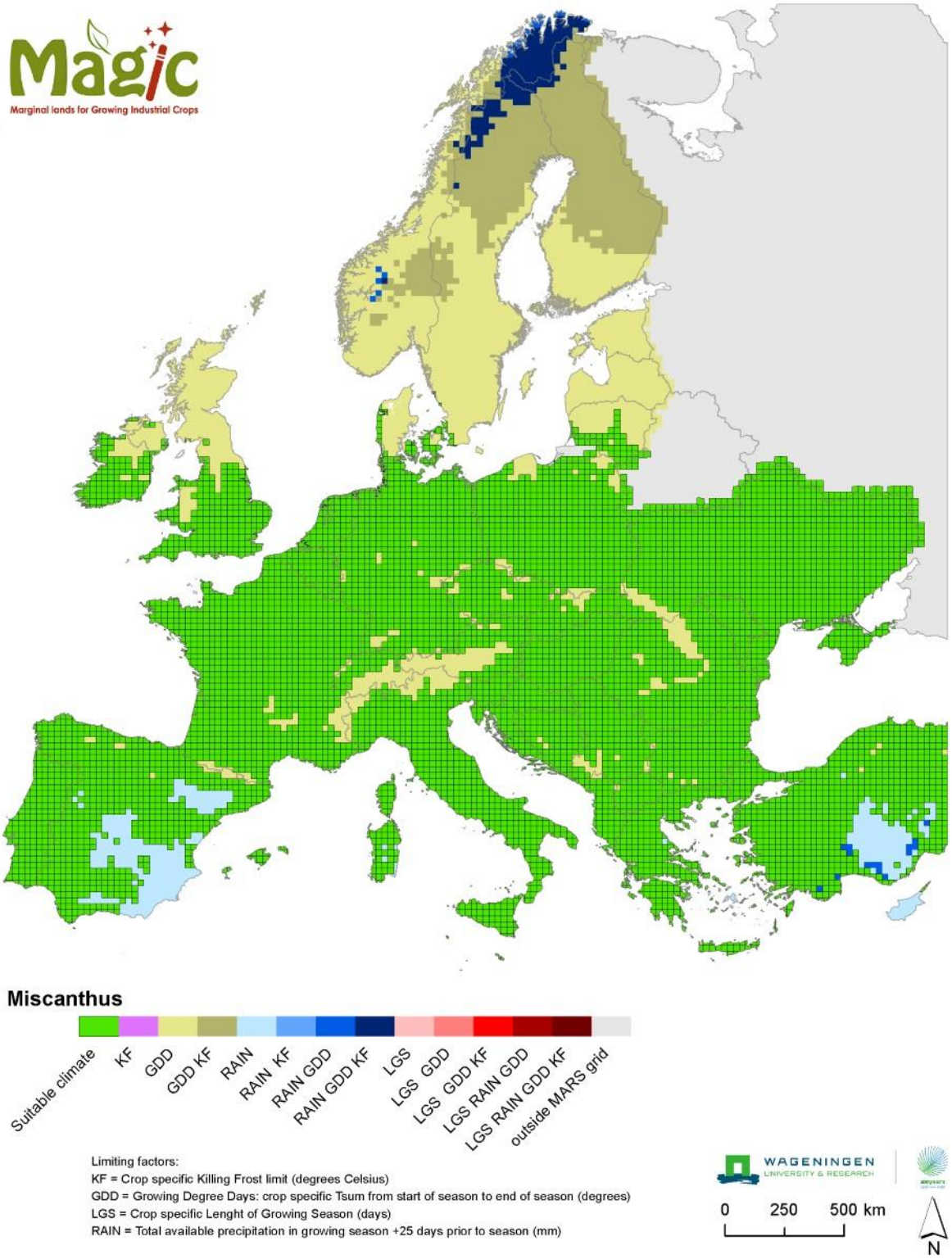

Figure 28: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for miscanthus based on climatic growth-suitability rankings presented in Chapter 2.

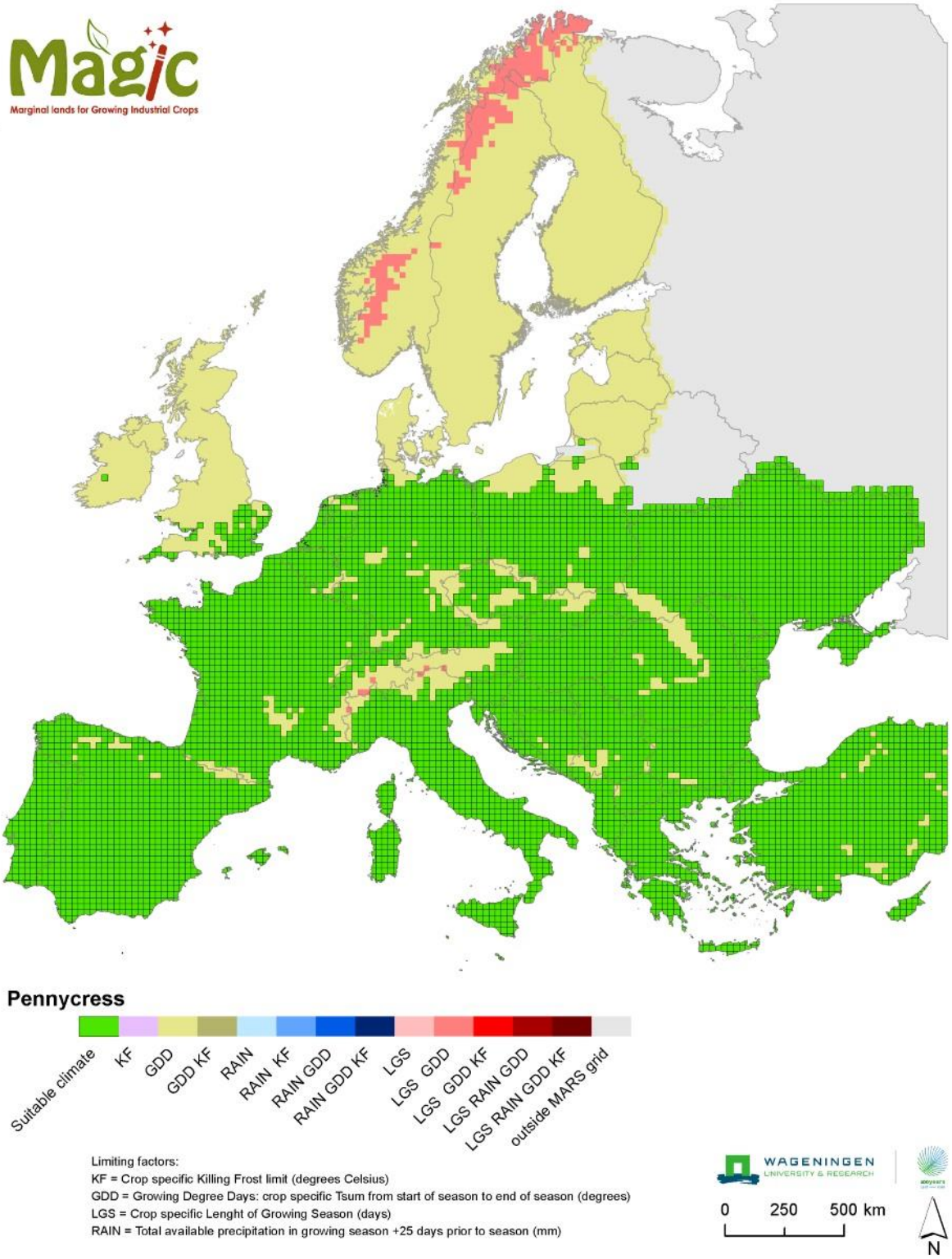

Figure 29: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for pennycress based on climatic growth-suitability rankings presented in Chapter 2.

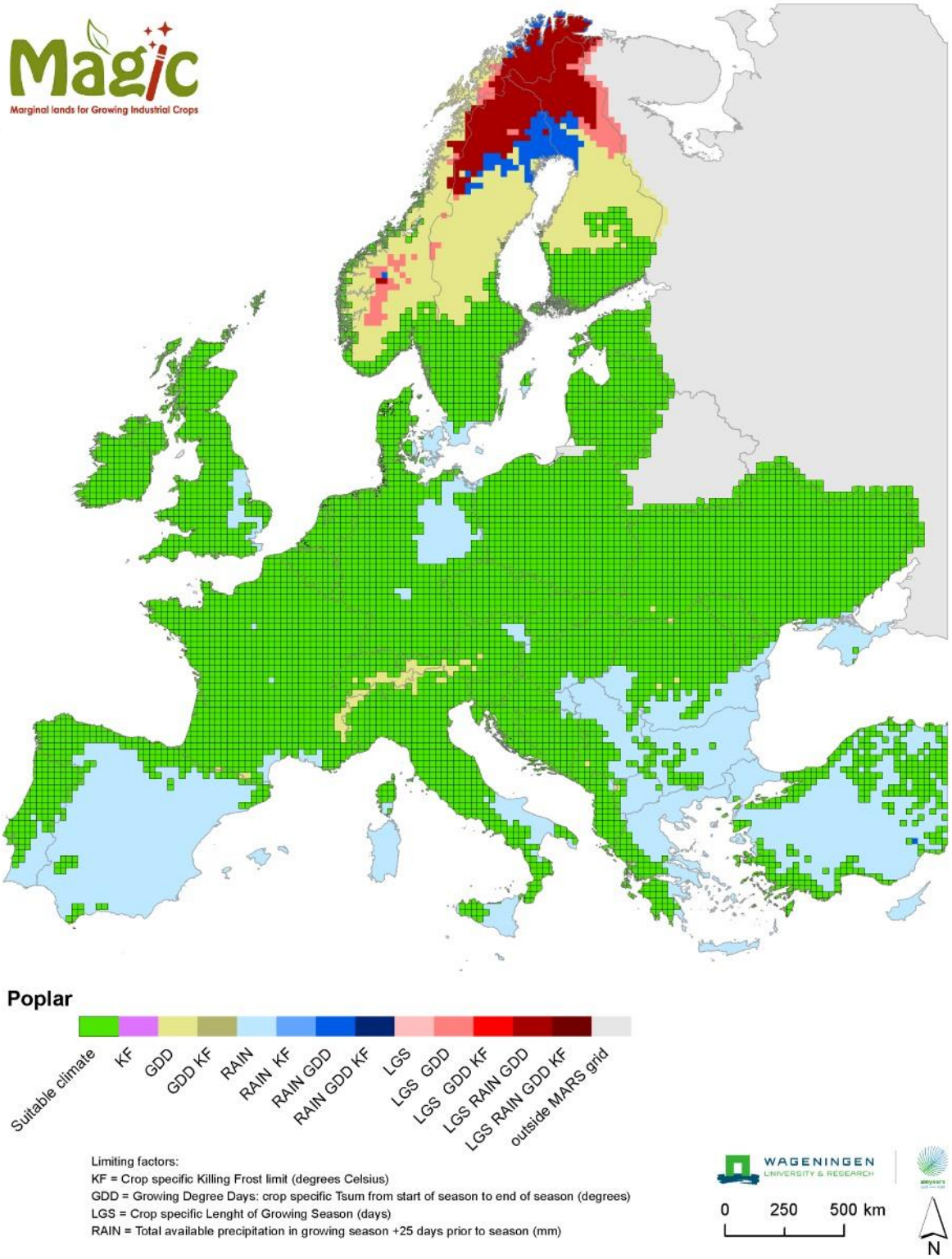

Figure 30: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for poplar based on climatic growth-suitability rankings presented in Chapter 2.

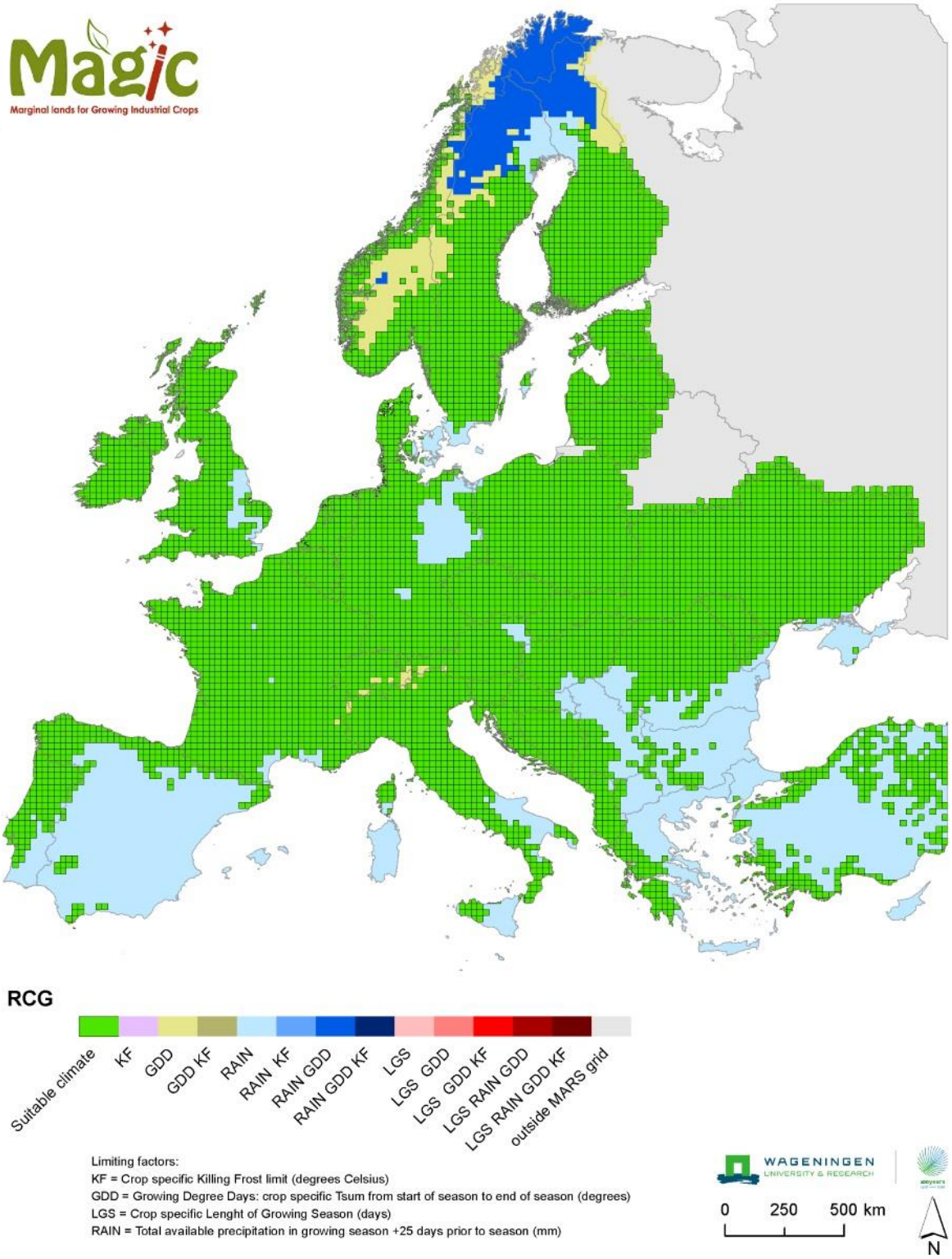

Figure 31: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for reed canary grass based on climatic growth-suitability rankings presented in Chapter 2.

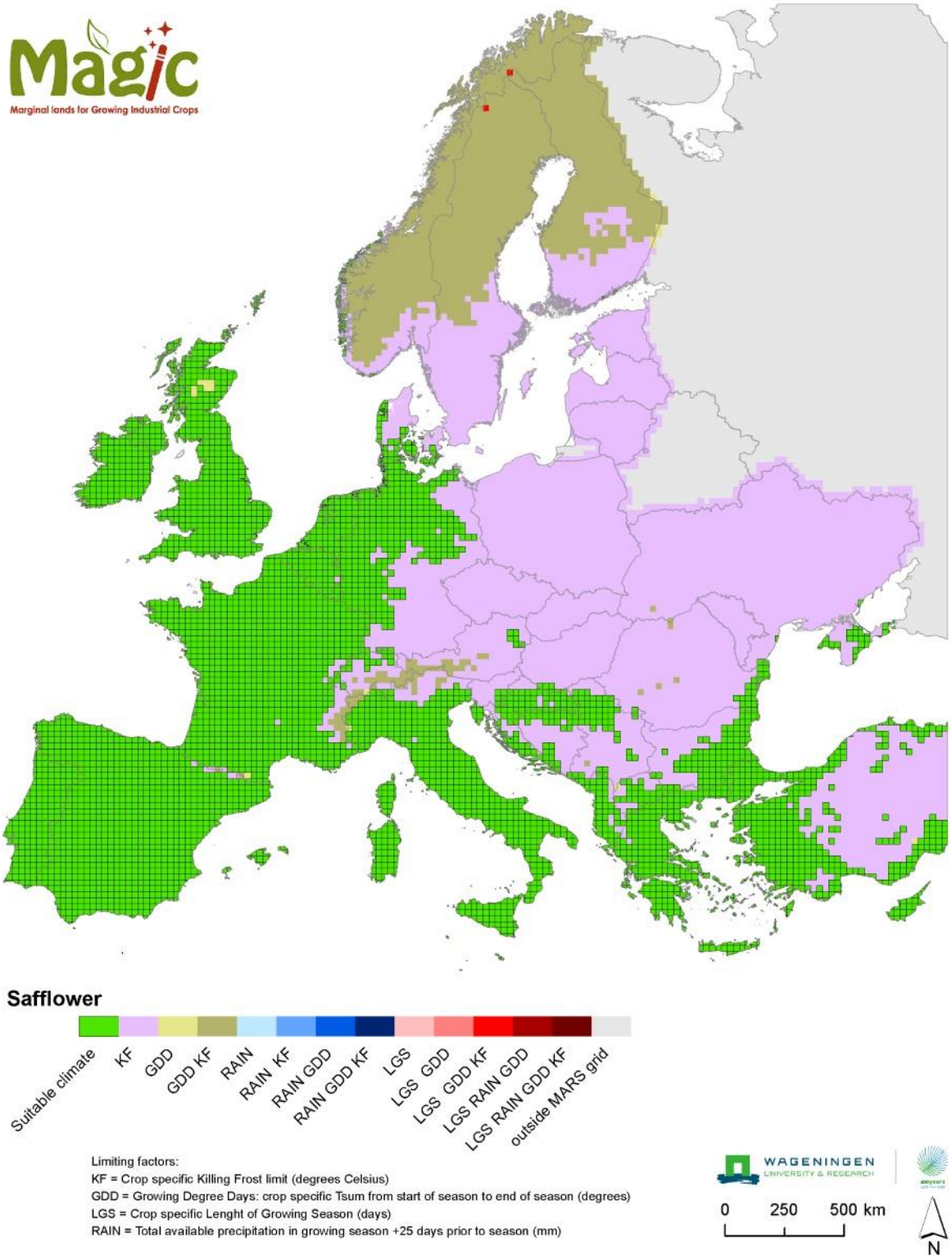

Figure 32: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for safflower based on climatic growth-suitability rankings presented in Chapter 2.

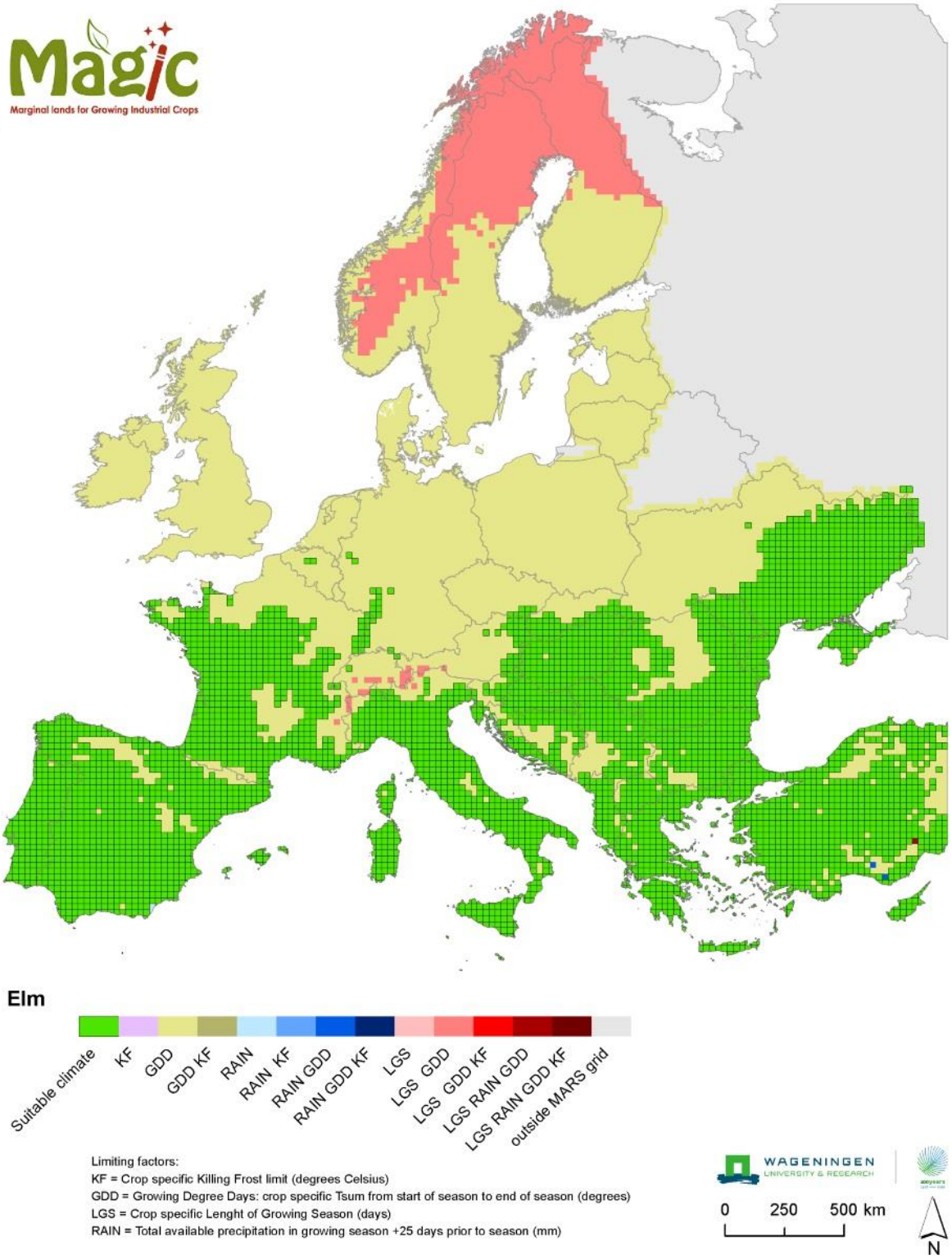

Figure 33: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for Siberian elm based on climatic growth-suitability rankings presented in Chapter 2.

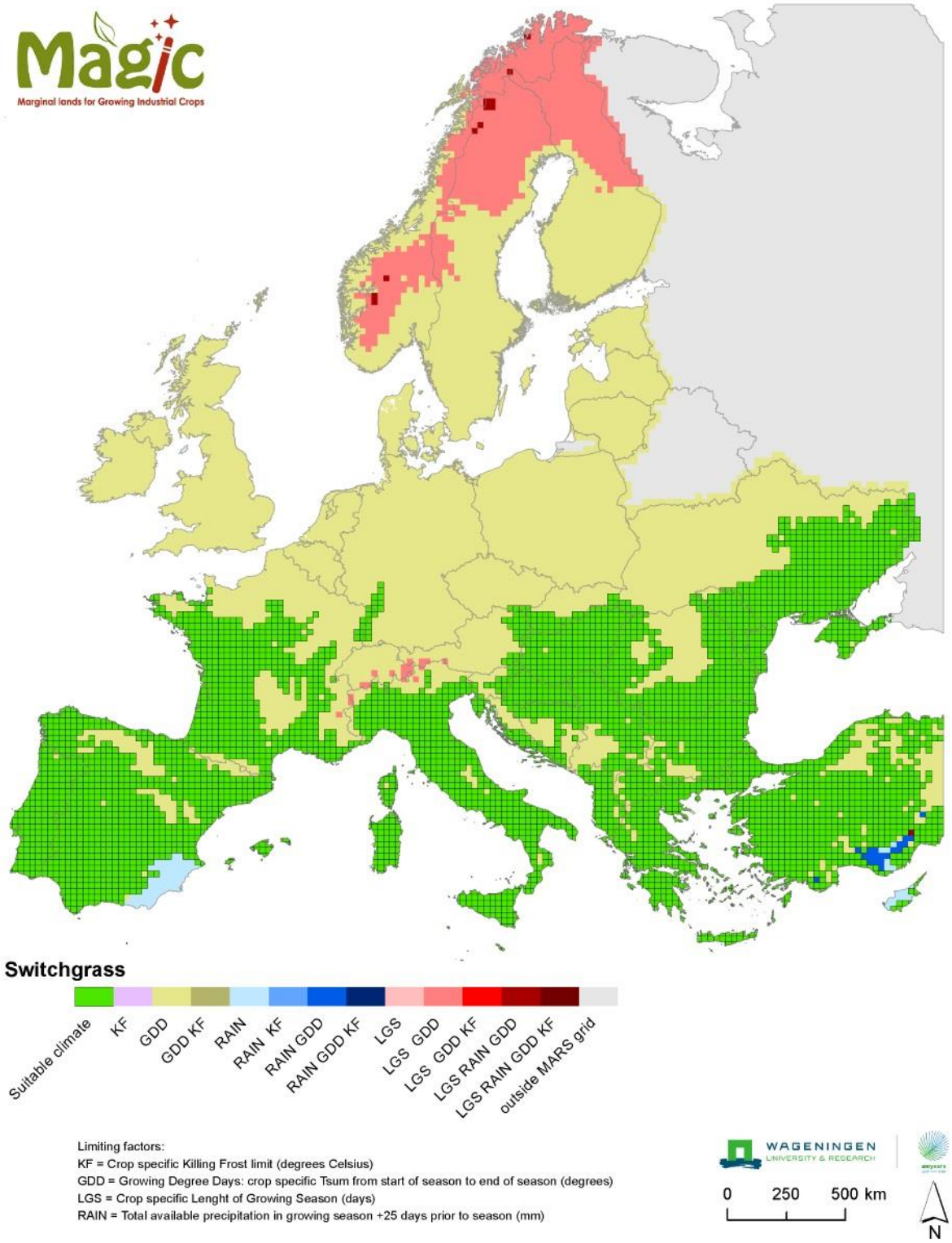

Figure 34: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for switchgrass based on climatic growth-suitability rankings presented in Chapter 2.

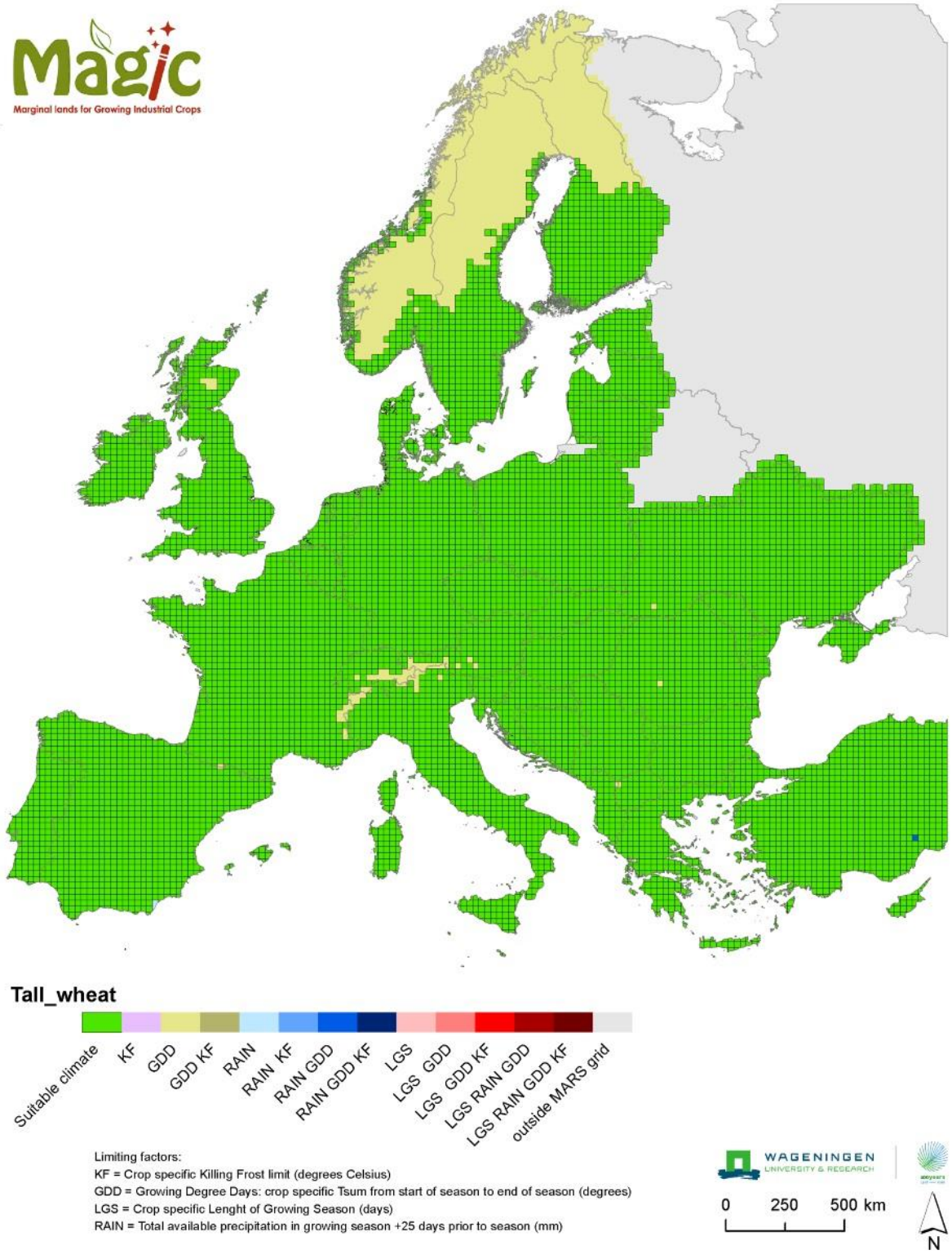

Figure 35: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for tall wheatgrass based on climatic growth-suitability rankings presented in Chapter 2.

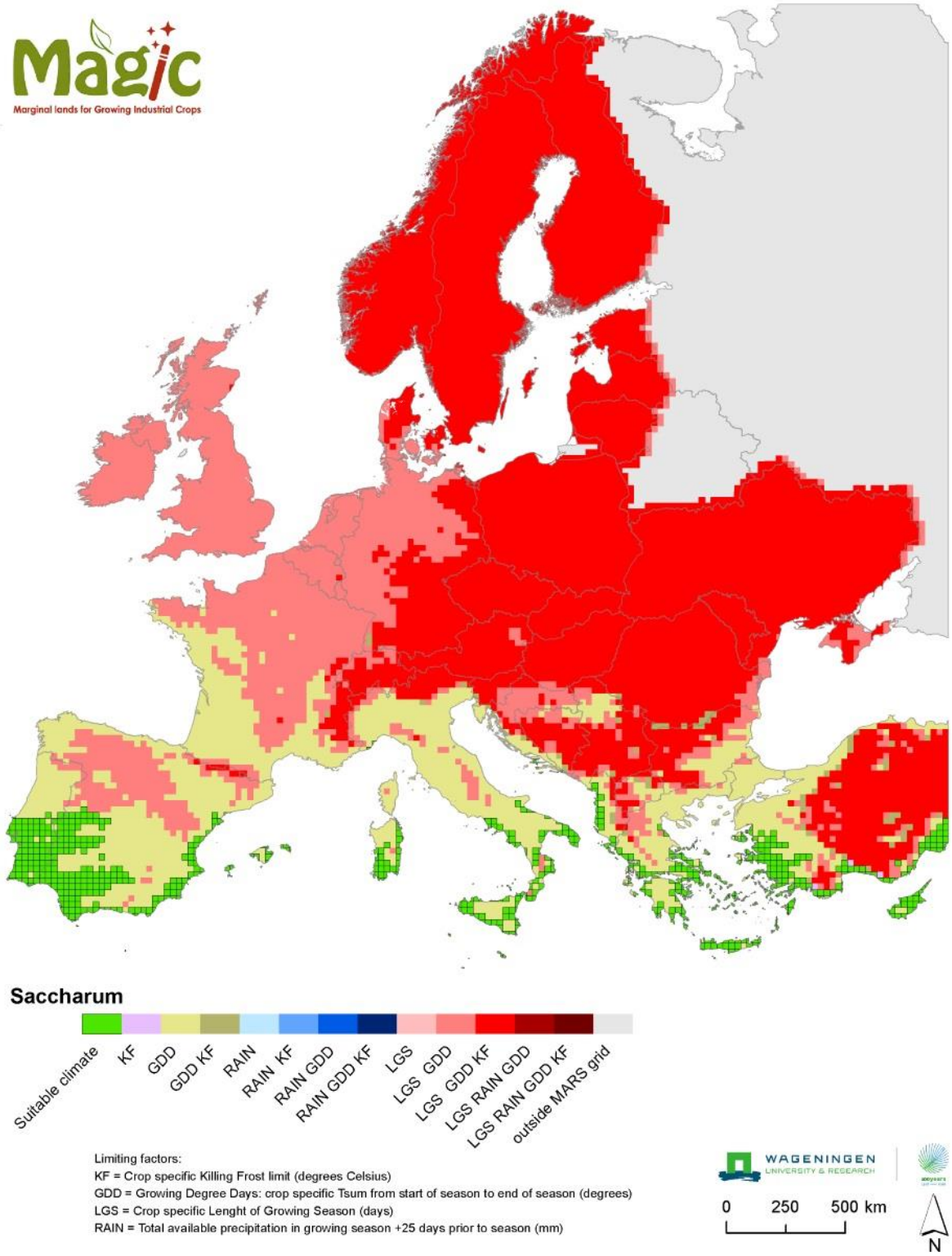

Figure 36: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for wild sugarcane based on climatic growth-suitability rankings presented in Chapter 2.

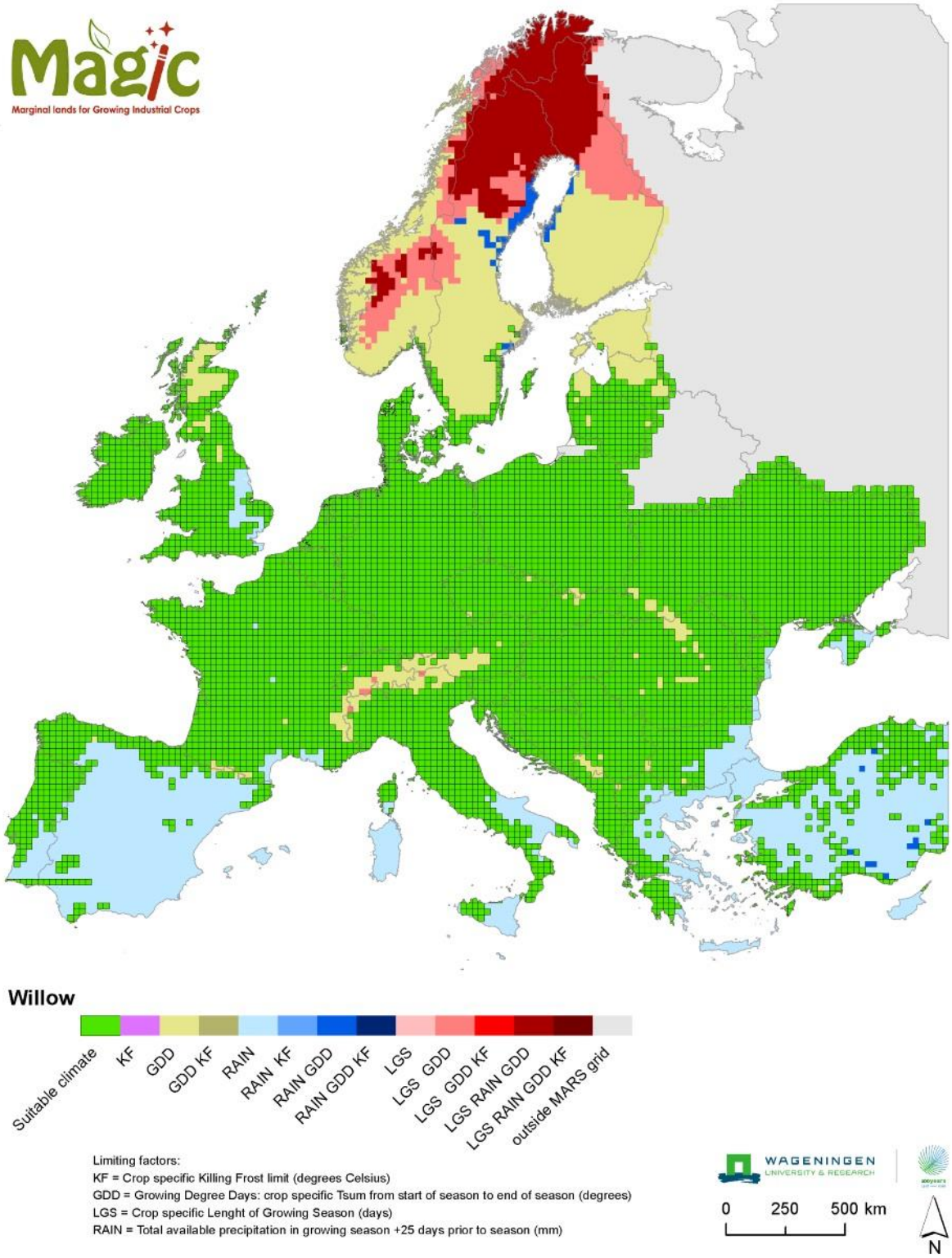

Figure 37: Spatial distribution of suitable climate conditions on both marginal and non-marginal land across Europe for willow based on climatic growth-suitability rankings presented in Chapter 2.

3.2.3. Overall (MAEZ-) growth suitability and expected performance of industrial crops across EU 28

In this section, the combined effects of climatic and soil conditions on marginal lands (MAEZ) on the crop-specific growth suitability will be presented. Therefore, the key results of crop-specific ranking per AEZ will be shown in absolute (km²) and relative (% of total marginal area per AEZ) values. MAEZ-specific maps were not provided in this study, because MAEZ are both rather small and heterogeneously distributed (Fig. 11-16) which would make it difficult to recognize anything on the map without the ability of zooming-in. However, crop-specific suitability maps for combined climate and soil/terrain growth conditions (all MAEZ together) are provided within the Annex (Fig. A 1-19) showing that these are quite comparable with climatic growth suitability maps (Fig. 19-37). Additionally, the expected overall performances of the industrial crops (Table 21) were added to the crop-specific growth-suitability rankings. The expected overall performances were based on the preliminary results of the multi-criteria analysis (Box 4.1.6).

Box 4.1.6 Expected overall performance of the selected industrial crops

After identification of industrial crops suitable to be cultivated under MAEZ-specific growth conditions using low-input practices (where environmental requirements will be considered), it is necessary to select the most feasible crops in a next step to guarantee maximum profit with the harvested material. This evaluation was done in WP 1 (Task 1.3) by developing a crop-specific ranking. For this ranking, five criteria were selected which were expected to be most relevant for the overall performance of both biomass production and processing (including distribution channels) (Table 22). For these criteria, crop-specific rankings were compiled based on literature and expert opinions.

It is highly recommended to take the expected overall performance of industrial crops under consideration for MALLIS development because the crop-selection can often result in more than one crop being suitable for a marginal area but there may be large differences in their overall and site-specific economic value under aspects of availability of processing industry, distance to distribution channels, infrastructure, etc.. For perennials, it is clear that only one crop can be chosen for cultivation. Thus, the economic ranking is highly relevant for the selection of a perennial industrial crop due to the long-term effect of the crop-selection. Whereas, for annual or winter-annual crops, the economic ranking might also be helpful in context of the conceptualizing of an optimal crop rotation system according to both growth suitability and economic feasibility. In this study, the output of the multi-criteria analysis (WP 1, Task 1.3) was used to take general economic values of the pre-selected industrial crops into consideration for MALLIS development, especially for MAEZ-specific recommendations. For site-specific MALLIS development, it has to be evaluated site- and

farm specifically whether the regional recommendation is also applicable on the field-to-farm scale.

Table 22: Preliminary results of the multi-criteria analysis (WP 1, Task 1.3) for the pre-selected industrial crops (Table 1). The crops performances per criterion were ranked based on expert opinions (1 = poor, 2 = fair, 3 = good, 4 = very good, 5 = excellent).

Crop	Experience with agricultural management of the proposed industrial crops (20%) *potential*	Crop productivity for industrial applications (according to the main uses) (20%) *potential*	Expected crop performance on marginal land (30%) *knowledge*	Industry demand (15%) *commercial*	Market opportunities (15%) *commercial*	Average
Biomass sorghum	4.8	4.8	4.5	4.3	4.8	4.6
Camelina	4.8	4.8	4.5	3.3	4.0	4.3
Cardoon	4.5	5.0	5.0	4.0	5.0	4.8
Castor	4.5	5.0	4.5	5.0	5.0	4.8
Crambe	3.8	3.8	3.5	2.8	2.0	3.3
Ethiopian mustard	4.5	4.5	4.5	4.5	4.5	4.5
Giant reed	4.5	5.0	5.0	4.5	5.0	4.8
Hemp	5.0	5.0	4.0	4.5	5.0	4.6
Lupin	4.3	3.5	2.8	3.5	3.5	3.4
Miscanthus	5.0	5.0	4.5	5.0	5.0	4.9
Pennycress	4.5	4.0	4.5	4.0	5.0	4.4
Poplar	4.5	4.3	4.5	4.0	3.8	4.3
Reed canary grass	5.0	5.0	5.0	4.0	4.0	4.7
Safflower	4.5	4.5	4.5	4.0	5.0	4.5
Siberian elm	4.0	4.0	4.5	4.5	5.0	4.4
Switchgrass	4.5	4.5	5.0	4.3	4.5	4.6
Tall wheatgrass	4.5	4.5	4.5	4.0	5.0	4.5
Wild sugarcane	3.5	4.0	5.0	4.5	4.5	4.4
Willow	4.8	4.3	4.5	4.0	3.8	4.3

The following Tables 23 – 29 provide detailed information on the overall crop-specific growth suitabilities according to both the total marginal area per AEZ (Table 23) and the 5 most relevant biophysical constraints (combinations) per AEZ (Tables 24-29). Wetness (WT, excess soil moisture or poor soil drainage) could not be mapped since it was not possible to develop a crop-specific suitability ranking (Chapter 2). Recommendations for MALLIS on those MAEZ which contain WT constraints are provided separately in Chapters 2 and 4. The preliminary results of the multi-criteria analysis (Table 22) were also added to Tables 23-29 to allow for a more realistic evaluation of the expected overall performance of the crops within each AEZ and MAEZ, respectively. This is important because in many cases there are multiple choices of crops being well adapted to the marginal conditions.

Table 23: Growth-suitabilities of the pre-selected industrial crops across MAEZ per AEZ under consideration of both climatic and soil conditions, which represents the total marginal area per AEZ. Biomass types: L = Lignocellulosic, M = Multipurpose, O = Oil, W = Wood. The expected overall performance of the crops (MCA) is indicated by the preliminary results of the multi-criteria analysis (adapted from WP1, Task 1.3). All values are colorized separately for each category. The crops are sorted by type (1st order) and km² (2nd order).

Mediterranean (AEZ 1)					Atlantic (AEZ 2)					Continental & boreal (AEZ 3)				
Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA
Tall wheatgrass	L	211,255	96	4.5	Tall wheatgrass	L	151,166	79	4.5	Tall wheatgrass	L	172,355	73	4.5
Switchgrass	L	160,238	73	4.6	Reed canary grass	L	124,821	65	4.7	Reed canary grass	L	147,470	63	4.7
Miscanthus	L	130,634	60	4.9	Miscanthus	L	83,820	44	4.9	Miscanthus	L	88,010	37	4.9
Giant reed	L	129,501	59	4.8	Switchgrass	L	19,732	10	4.6	Switchgrass	L	26,628	11	4.6
Wild sugarcane	L	46,768	21	4.4	Giant reed	L	2,459	1	4.8	Giant reed	L	1,173	1	4.8
Reed canary grass	L	45,863	21	4.7	Wild sugarcane	L	252	<0.5	4.4	Wild sugarcane	L	0	0	4.4
Lupin	M	201,888	92	3.4	Hemp	M	80,422	42	4.6	Cardoon	M	82,607	35	4.8
Biomass sorghum	M	193,118	88	4.6	Cardoon	M	71,822	37	4.8	Lupin	M	37,162	16	3.4
Cardoon	M	172,804	79	4.8	Lupin	M	36,790	19	3.4	Hemp	M	17,392	7	4.6
Hemp	M	162,794	74	4.6	Biomass sorghum	M	31,322	16	4.6	Biomass sorghum	M	6,323	3	4.6
Crambe	O	216,577	99	3.3	Camelina	O	186,018	97	4.3	Safflower	O	16,164	7	4.5
Camelina	O	209,761	96	4.3	Crambe	O	175,244	91	3.3	Camelina	O	183,667	78	4.3
Pennycress	O	208,388	95	4.4	Safflower	O	145,382	76	4.5	Crambe	O	130,959	66	3.3
Ethiopian mustard	O	184,988	84	4.5	Pennycress	O	64,812	34	4.4	Pennycress	O	76,465	33	4.4
Castor bean	O	160,990	74	4.8	Ethiopian mustard	O	43,177	23	4.5	Ethiopian mustard	O	10,111	4	4.5
Safflower	O	201,689	92	4.5	Castor bean	O	10,658	6	4.8	Castor bean	O	3,412	2	4.8
Siberian elm	W	179,148	82	4.4	Willow	W	164,191	86	4.3	Poplar	W	150,428	64	4.3
Willow	W	56,880	26	4.3	Poplar	W	159,930	83	4.3	Willow	W	119,536	51	4.3
Poplar	W	48,166	22	4.3	Siberian elm	W	20,611	11	4.4	Siberian elm	W	28,261	12	4.4

Table 24: Growth-suitability of industrial crops on marginal land only affected by adverse rooting conditions (RT: shallow rooting depth or unfavourable texture; MAEZ: combination of RT and AEZ). Biomass types: L = Lignocellulosic, M = Multipurpose, O = Oil, W = Wood. The expected overall performance of the crops (MCA) is indicated by the preliminary results of the multi-criteria analysis (adapted from WP1, Task 1.3). All values are colorized separately for each category. The crops are sorted by type (1st order) and km² (2nd order).

MAEZ: RT_1					MAEZ: RT_2					MAEZ: RT_3					RT_{TOTAL}				
Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA
Tall wheatgrass	L	62,246	100	4.5	Tall wheatgrass	L	51,817	100	4.5	Tall wheatgrass	L	41,449	100	4.5	Tall wheatgrass	L	155,512	100	4.5
Miscanthus	L	43,155	69	4.9	Reed canary grass	L	35,761	69	4.7	Reed canary grass	L	30,985	75	4.7	Miscanthus	L	98,960	64	4.9
Switchgrass	L	41,611	67	4.6	Miscanthus	L	32,179	62	4.9	Miscanthus	L	23,626	57	4.9	Reed canary grass	L	82,343	53	4.7
Giant reed	L	27,107	44	4.8	Switchgrass	L	9,314	18	4.6	Switchgrass	L	3,480	8	4.6	Switchgrass	L	54,405	35	4.6
Reed canary grass	L	15,597	25	4.7	Giant reed	L	743	1	4.8	Giant reed	L	381	1	4.8	Giant reed	L	28,231	18	4.8
Wild sugarcane	L	9,701	16	4.4	Wild sugarcane	L	199	<0.5	4.4	Wild sugarcane	L	0	0	4.4	Wild sugarcane	L	9,900	6	4.4
Biomass sorghum	M	56,136	90	4.6	Hemp	M	33,691	65	4.6	Cardoon	M	26,336	64	4.8	Cardoon	M	105,837	68	4.8
Lupin	M	55,383	89	3.4	Cardoon	M	32,776	63	4.8	Lupin	M	6,913	17	3.4	Hemp	M	82,384	53	4.6
Cardoon	M	46,725	75	4.8	Lupin	M	19,546	38	3.4	Hemp	M	2,524	6	4.6	Lupin	M	81,842	53	3.4
Hemp	M	46,169	74	4.6	Biomass sorghum	M	18,491	36	4.6	Biomass sorghum	M	1,314	3	4.6	Biomass sorghum	M	75,941	49	4.6
Camelina	O	62,246	100	4.3	Camelina	O	51,817	100	4.3	Camelina	O	41,449	100	4.3	Camelina	O	155,512	100	4.3
Crambe	O	62,246	100	3.3	Crambe	O	51,795	100	3.3	Crambe	O	33,971	82	3.3	Crambe	O	148,012	95	3.3
Pennycress	O	62,009	100	4.4	Safflower	O	49,849	96	4.5	Pennycress	O	24,751	60	4.4	Pennycress	O	119,967	77	4.4
Safflower	O	60,880	98	4.5	Pennycress	O	33,207	64	4.4	Safflower	O	3,896	9	4.5	Safflower	O	114,625	74	4.5
Ethiopian mustard	O	45,247	73	4.5	Ethiopian mustard	O	19,941	38	4.5	Castor	O	888	2	4.8	Ethiopian mustard	O	66,013	42	4.5
Castor	O	39,008	63	4.8	Castor	O	5,580	11	4.8	Ethiopian mustard	O	825	2	4.5	Castor	O	45,476	29	4.8
Siberian elm	W	43,016	69	4.4	Willow	W	51,379	99	4.3	Willow	W	39,784	96	4.3	Willow	W	113,376	73	4.3
Willow	W	22,213	36	4.3	Poplar	W	35,761	69	4.3	Poplar	W	30,985	75	4.3	Poplar	W	82,343	53	4.3
Poplar	W	15,597	25	4.3	Siberian elm	W	9,757	19	4.4	Siberian elm	W	4,250	10	4.4	Siberian elm	W	57,023	37	4.4

Table 25: Growth-suitability of industrial crops on marginal land only affected by adverse terrain conditions (TR: steep slope; MAEZ: combination of TR and AEZ). Biomass types: L = Lignocellulosic, M = Multipurpose, O = Oil, W = Wood. The expected overall performance of the crops (MCA) is indicated by the preliminary results of the multi-criteria analysis (adapted from WP1, Task 1.3). All values are colorized separately for each category. The crops are sorted by type (1st order) and km² (2nd order).

MAEZ: TR_1					MAEZ: TR_2					MAEZ: TR_3					TR_{TOTAL}				
Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA
Tall wheatgrass	L	29,708	95	4.5	Tall wheatgrass	L	5,365	94	4.5	Tall wheatgrass	L	11,174	98	4.5	Tall wheatgrass	L	46,247	96	4.5
Miscanthus	L	28,902	92	4.9	Reed canary grass	L	5,273	92	4.7	Miscanthus	L	10,707	94	4.9	Miscanthus	L	44,409	92	4.9
Switchgrass	L	28,015	89	4.6	Miscanthus	L	4,800	84	4.9	Reed canary grass	L	9,116	80	4.7	Switchgrass	L	36,181	75	4.6
Reed canary grass	L	19,312	62	4.7	Switchgrass	L	2,281	40	4.6	Switchgrass	L	5,885	52	4.6	Reed canary grass	L	33,701	70	4.7
Giant reed	L	19,194	61	4.8	Giant reed	L	230	4	4.8	Giant reed	L	201	2	4.8	Giant reed	L	19,625	41	4.8
Wild sugarcane	L	6,721	21	4.4	Wild sugarcane	L	0	0	4.4	Wild sugarcane	L	0	0	4.4	Wild sugarcane	L	6,721	14	4.4
Cardoon	M	29,444	94	4.8	Cardoon	M	4,655	82	4.8	Cardoon	M	10,849	95	4.8	Cardoon	M	44,948	93	4.8
Lupin	M	28,355	90	3.4	Hemp	M	4,111	72	4.6	Lupin	M	6,016	53	3.4	Lupin	M	36,845	76	3.4
Biomass sorghum	M	28,004	89	4.6	Biomass sorghum	M	2,533	44	4.6	Hemp	M	1,563	14	4.6	Biomass sorghum	M	31,448	65	4.6
Hemp	M	19,299	62	4.6	Lupin	M	2,474	43	3.4	Biomass sorghum	M	911	8	4.6	Hemp	M	24,973	52	4.6
Camelina	O	31,331	100	4.3	Camelina	O	5,705	100	4.3	Camelina	O	11,362	100	4.3	Camelina	O	48,398	100	4.3
Crambe	O	31,325	100	3.3	Crambe	O	5,616	98	3.3	Crambe	O	11,098	98	3.3	Crambe	O	48,039	99	3.3
Pennycress	O	30,982	99	4.4	Safflower	O	5,300	93	4.5	Pennycress	O	10,166	89	4.4	Pennycress	O	45,371	94	4.4
Safflower	O	29,217	93	4.5	Pennycress	O	4,223	74	4.4	Safflower	O	1,596	14	4.5	Safflower	O	36,113	75	4.5
Ethiopian mustard	O	28,698	92	4.5	Ethiopian mustard	O	3,381	59	4.5	Ethiopian mustard	O	1,286	11	4.5	Ethiopian mustard	O	33,365	69	4.5
Castor	O	26,013	83	4.8	Castor	O	900	16	4.8	Castor	O	498	4	4.8	Castor	O	27,411	57	4.8
Siberian elm	W	28,361	91	4.4	Poplar	W	5,612	98	4.3	Willow	W	10,973	97	4.3	Siberian elm	W	37,207	77	4.4
Poplar	W	20,291	65	4.3	Willow	W	5,201	91	4.3	Poplar	W	9,241	81	4.3	Willow	W	35,661	74	4.3
Willow	W	19,487	62	4.3	Siberian elm	W	2,522	44	4.4	Siberian elm	W	6,324	56	4.4	Poplar	W	35,144	73	4.3

Table 26: Growth-suitability of industrial crops on marginal land only affected by climatic limitations (CL: low temperature, short vegetation period or dryness; MAEZ: combination of CL and AEZ). Biomass types: L = Lignocellulosic, M = Multipurpose, O = Oil, W = Wood. The expected overall performance of the crops (MCA) is indicated by the preliminary results of the multi-criteria analysis (adapted from WP1, Task 1.3). All values are colorized separately for each category. The crops are sorted by type (1st order) and km² (2nd order).

MAEZ: CL_1					MAEZ: CL_2					MAEZ: CL_3					CL_{TOTAL}				
Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA
Tall wheatgrass	L	27,678	100	4.5	Reed canary grass	L	4,561	100	4.7	Tall wheatgrass	L	60,055	75	4.5	Tall wheatgrass	L	91,711	82	4.5
Switchgrass	L	24,462	88	4.6	Tall wheatgrass	L	3,978	87	4.5	Reed canary grass	L	59,851	75	4.7	Reed canary grass	L	64,717	58	4.7
Giant reed	L	21,988	79	4.8	Miscanthus	L	30	1	4.9	Miscanthus	L	461	1	4.9	Switchgrass	L	24,572	22	4.6
Miscanthus	L	12,499	45	4.9	Switchgrass	L	3	<0.5	4.6	Switchgrass	L	107	<0.5	4.6	Giant reed	L	22,009	20	4.8
Wild sugarcane	L	7,659	28	4.4	Giant reed	L	0	0	4.8	Giant reed	L	21	<0.5	4.8	Miscanthus	L	12,990	12	4.9
Reed canary grass	L	305	1	4.7	Wild sugarcane	L	0	0	4.4	Wild sugarcane	L	0	0	4.4	Wild sugarcane	L	7,659	7	4.4
Hemp	M	27,721	100	4.6	Cardoon	M	29	1	4.8	Cardoon	M	2,783	3	4.8	Cardoon	M	27,919	25	4.8
Lupin	M	27,582	99	3.4	Hemp	M	23	1	4.6	Lupin	M	109	<0.5	3.4	Hemp	M	27,826	25	4.6
Biomass sorghum	M	27,569	99	4.6	Biomass sorghum	M	3	<0.5	4.6	Hemp	M	82	<0.5	4.6	Lupin	M	27,694	25	3.4
Cardoon	M	25,107	90	4.8	Lupin	M	3	<0.5	3.4	Biomass sorghum	M	50	<0.5	4.6	Biomass sorghum	M	27622	25	4.6
Camelina	O	27,752	100	4.3	Camelina	O	3,979	87	4.3	Camelina	O	61,055	77	4.3	Camelina	O	92,786	83	4.3
Crambe	O	27,752	100	3.3	Safflower	O	3,926	86	4.5	Crambe	O	23,959	30	3.3	Crambe	O	54,093	48	3.3
Safflower	O	27,740	100	4.5	Crambe	O	2,382	52	3.3	Safflower	O	496	1	4.5	Safflower	O	32,162	29	4.5
Pennycress	O	27,731	100	4.4	Pennycress	O	8	<0.5	4.4	Pennycress	O	322	<0.5	4.4	Pennycress	O	28,061	25	4.4
Ethiopian mustard	O	27,620	100	4.5	Ethiopian mustard	O	3	<0.5	4.5	Ethiopian mustard	O	87	<0.5	4.5	Ethiopian mustard	O	27,710	25	4.5
Castor	O	24,998	90	4.8	Castor	O	1	<0.5	4.8	Castor	O	39	<0.5	4.8	Castor	O	25,038	22	4.8
Siberian elm	W	27,508	99	4.4	Poplar	W	4,562	100	4.3	Poplar	W	51,159	64	4.3	Poplar	W	56,026	50	4.3
Willow	W	850	3	4.3	Willow	W	1,718	38	4.3	Willow	W	7,400	9	4.3	Siberian elm	W	27,644	25	4.4
Poplar	W	305	1	4.3	Siberian elm	W	3	<0.5	4.4	Siberian elm	W	133	<0.5	4.4	Willow	W	9,968	9	4.3

Table 27: Growth-suitability of industrial crops on marginal land only affected by combined climatic and rooting conditions (CL_RT: low temperature, short vegetation period or dryness and shallow rooting depth or unfavourable texture; MAEZ: combination of CL_RT and AEZ). Biomass types: L = Lignocellulosic, M = Multipurpose, O = Oil, W = Wood. The expected overall performance of the crops (MCA) is indicated by the preliminary results of the multi-criteria analysis (adapted from WP1, Task 1.3). All values are colorized separately for each category. The crops are sorted by type (1st order) and km² (2nd order).

MAEZ: CL_RT_1					MAEZ: CL_RT_2					MAEZ: CL_RT_3					CL_RT_{TOTAL}				
Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA
Tall wheatgrass	L	25,674	100	4.5	Reed canary grass	L	434	73	4.7	Tall wheatgrass	L	5,553	92	4.5	Tall wheatgrass	L	31,645	98	4.5
Switchgrass	L	22,315	87	4.6	Tall wheatgrass	L	418	70	4.5	Reed canary grass	L	4,860	80	4.7	Switchgrass	L	22,347	69	4.6
Miscanthus	L	15,635	61	4.9	Miscanthus	L	8	1	4.9	Miscanthus	L	51	1	4.9	Miscanthus	L	15,694	49	4.9
Giant reed	L	12,210	48	4.8	Switchgrass	L	5	1	4.6	Switchgrass	L	27	<0.5	4.6	Giant reed	L	12,225	38	4.8
Wild sugarcane	L	3,590	14	4.4	Giant reed	L	1	<0.5	4.8	Giant reed	L	14	<0.5	4.8	Reed canary grass	L	5,554	17	4.7
Reed canary grass	L	260	1	4.7	Wild sugarcane	L	0	0	4.4	Wild sugarcane	L	0	0	4.4	Wild sugarcane	L	3,590	11	4.4
Biomass sorghum	M	25,467	99	4.6	Biomass sorghum	M	23	4	4.6	Cardoon	M	316	5	4.8	Biomass sorghum	M	25,508	79	4.6
Lupin	M	25,445	99	3.4	Lupin	M	23	4	3.4	Lupin	M	28	<0.5	3.4	Lupin	M	25,496	79	3.4
Hemp	M	23,302	91	4.6	Hemp	M	8	1	4.6	Hemp	M	22	<0.5	4.6	Hemp	M	23,332	72	4.6
Cardoon	M	22,936	89	4.8	Cardoon	M	6	1	4.8	Biomass sorghum	M	18	<0.5	4.6	Cardoon	M	23,258	72	4.8
Camelina	O	25,675	100	4.3	Camelina	O	418	70	4.3	Camelina	O	5,553	92	4.3	Camelina	O	31,646	98	4.3
Crambe	O	25,675	100	3.3	Safflower	O	408	69	4.5	Crambe	O	1,538	25	3.3	Crambe	O	27,378	85	3.3
Pennycress	O	25,665	100	4.4	Crambe	O	165	28	3.3	Pennycress	O	52	1	4.4	Safflower	O	26,074	81	4.5
Safflower	O	25,635	100	4.5	Pennycress	O	26	4	4.4	Safflower	O	31	1	4.5	Pennycress	O	25,743	80	4.4
Ethiopian mustard	O	23,268	91	4.5	Castor	O	9	2	4.8	Castor	O	18	<0.5	4.8	Ethiopian mustard	O	23,289	72	4.5
Castor	O	19,184	75	4.8	Ethiopian mustard	O	5	1	4.5	Ethiopian mustard	O	16	<0.5	4.5	Castor	O	19,211	59	4.8
Siberian elm	W	23,214	90	4.4	Poplar	W	434	73	4.3	Poplar	W	4,793	79	4.3	Siberian elm	W	23,246	72	4.4
Willow	W	553	2	4.3	Willow	W	124	21	4.3	Willow	W	782	13	4.3	Poplar	W	5,487	17	4.3
Poplar	W	260	1	4.3	Siberian elm	W	5	1	4.4	Siberian elm	W	27	<0.5	4.4	Willow	W	1,459	5	4.3

Table 28: Growth-suitability of industrial crops on marginal land only affected by poor soil fertility conditions (FE: soil acidity, soil alkalinity or low content of soil organic carbon; MAEZ: combination of FE and AEZ). Biomass types: L = Lignocellulosic, M = Multipurpose, O = Oil, W = Wood. The expected overall performance of the crops (MCA) is indicated by the preliminary results of the multi-criteria analysis (adapted from WP1, Task 1.3). All values are colorized separately for each category. The crops are sorted by type (1st order) and km² (2nd order).

MAEZ: FE_1					MAEZ: FE_2					MAEZ: FE_3					FE_{TOTAL}				
Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA
Tall wheatgrass	L	15,201	100	4.5	Tall wheatgrass	L	3,070	99	4.5	Tall wheatgrass	L	5,245	100	4.5	Tall wheatgrass	L	23,516	100	4.5
Giant reed	L	11,616	76	4.8	Reed canary grass	L	3,067	99	4.7	Reed canary grass	L	5,135	98	4.7	Miscanthus	L	13,575	58	4.9
Switchgrass	L	11,102	73	4.6	Miscanthus	L	2,976	96	4.9	Miscanthus	L	4,807	92	4.9	Switchgrass	L	12,345	52	4.6
Miscanthus	L	5,792	38	4.9	Switchgrass	L	114	4	4.6	Switchgrass	L	1,129	22	4.6	Giant reed	L	11,621	49	4.8
Wild sugarcane	L	3,431	23	4.4	Giant reed	L	1	<0.5	4.8	Giant reed	L	4	<0.5	4.8	Reed canary grass	L	9,648	41	4.7
Reed canary grass	L	1,446	10	4.7	Wild sugarcane	L	0	0	4.4	Wild sugarcane	L	0	0	4.4	Wild sugarcane	L	3,431	15	4.4
Lupin	M	15,185	100	3.4	Cardoon	M	2,959	96	4.8	Cardoon	M	5,148	98	4.8	Cardoon	M	20,488	87	4.8
Biomass sorghum	M	15,125	99	4.6	Hemp	M	2,940	95	4.6	Lupin	M	1,133	22	3.4	Hemp	M	18,278	78	4.6
Hemp	M	15,120	99	4.6	Lupin	M	311	10	3.4	Hemp	M	218	4	4.6	Lupin	M	16,629	71	3.4
Cardoon	M	12,381	81	4.8	Biomass sorghum	M	298	10	4.6	Biomass sorghum	M	14	<0.50	4.6	Biomass sorghum	M	15,437	66	4.6
Camelina	O	15,205	100	4.3	Camelina	O	3,087	100	4.3	Camelina	O	5,246	100	4.3	Camelina	O	23,538	100	4.3
Crambe	O	15,205	100	3.3	Crambe	O	3,080	100	3.3	Crambe	O	5,208	99	3.3	Crambe	O	23,493	100	3.3
Pennycress	O	15,205	100	4.4	Safflower	O	2,982	97	4.5	Pennycress	O	4,035	77	4.4	Pennycress	O	22,036	94	4.4
Safflower	O	15,132	100	4.5	Pennycress	O	2,796	91	4.4	Safflower	O	219	4	4.5	Safflower	O	18,333	78	4.5
Ethiopian mustard	O	15,131	100	4.5	Ethiopian mustard	O	2,570	83	4.5	Ethiopian mustard	O	90	2	4.5	Ethiopian mustard	O	17,791	76	4.5
Castor	O	14,202	93	4.8	Castor	O	10	0	4.8	Castor	O	8	<0.5	4.8	Castor	O	14,220	60	4.8
Siberian elm	W	15,181	100	4.4	Poplar	W	3,084	100	4.3	Willow	W	5,197	99	4.3	Siberian elm	W	16,559	70	4.4
Willow	W	1,460	10	4.3	Willow	W	3,072	100	4.3	Poplar	W	5,136	98	4.3	Willow	W	9,729	41	4.3
Poplar	W	1,446	10	4.3	Siberian elm	W	245	8	4.4	Siberian elm	W	1,133	22	4.4	Poplar	W	9,666	41	4.3

Table 29: Growth-suitability of industrial crops on marginal land only affected by combined climatic and rooting conditions (CH: low temperature, short vegetation period or dryness and shallow rooting depth or unfavourable texture; MAEZ: combination of CH and AEZ). Biomass types: L = Lignocellulosic, M = Multipurpose, O = Oil, W = Wood. The expected overall performance of the crops (MCA) is indicated by the preliminary results of the multi-criteria analysis (adapted from WP1, Task 1.3). All values are colorized separately for each category. The crops are sorted by type (1st order) and km² (2nd order).

MAEZ: CH_1					MAEZ: CH_2					MAEZ: CH_3					CH_{TOTAL}				
Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA
Switchgrass	L	5,194	75	4.6	Miscanthus	L	2,065	57	4.9	Miscanthus	L	6,676	56	4.9	Miscanthus	L	13,933	62	4.9
Tall wheatgrass	L	5,194	75	4.5	Reed canary grass	L	2,038	56	4.7	Tall wheatgrass	L	6,600	55	4.5	Tall wheatgrass	L	13,832	61	4.5
Miscanthus	L	5,192	75	4.9	Tall wheatgrass	L	2,038	56	4.5	Switchgrass	L	6,273	52	4.6	Switchgrass	L	13,364	59	4.6
Giant reed	L	5,191	75	4.8	Switchgrass	L	1,897	52	4.6	Reed canary grass	L	4,046	34	4.7	Reed canary grass	L	7,877	35	4.7
Wild sugarcane	L	3,075	45	4.4	Giant reed	L	547	15	4.8	Giant reed	L	494	4	4.8	Giant reed	L	6,232	28	4.8
Reed canary grass	L	1,793	26	4.7	Wild sugarcane	L	53	1	4.4	Wild sugarcane	L	0	0	4.4	Wild sugarcane	L	3,128	14	4.4
Lupin	M	6,883	100	3.4	Lupin	M	3,493	96	3.4	Lupin	M	11,609	97	3.4	Lupin	M	21,985	98	3.4
Cardoon	M	5,194	75	4.8	Cardoon	M	2,038	56	4.8	Cardoon	M	6,600	55	4.8	Cardoon	M	13,832	61	4.8
Ethiopian mustard	O	6,878	100	4.5	Ethiopian mustard	O	3,614	99	4.5	Crambe	O	6,619	55	3.3	Crambe	O	13,878	62	3.3
Crambe	O	5,194	75	3.3	Crambe	O	2,065	57	3.3	Ethiopian mustard	O	1,089	9	4.5	Ethiopian mustard	O	11,581	51	4.5
Siberian elm	W	5,194	75	4.4	Poplar	W	2,065	57	4.3	Siberian elm	W	6,343	53	4.4	Siberian elm	W	13,453	60	4.4
Willow	W	1,883	27	4.3	Willow	W	2,065	57	4.3	Willow	W	6,284	52	4.3	Willow	W	10,232	45	4.3
Poplar	W	1,793	26	4.3	Siberian elm	W	1,916	53	4.4	Poplar	W	4,118	34	4.3	Poplar	W	7,976	35	4.3

4. MALLIS for industrial crops

In this section, we will provide recommendations for MALLIS at both regional (MAEZ) and field-to-farm scale. For regional scale, the most prevalent (top 3) MAEZ (Tables 15, 16, 19) will be considered. This will be done in Section 4.1. For field-to-farm scale, the specific site and farm conditions of existing and planned field trials will be considered for MALLIS development. Therefore, Section 4.1 starts with the development of MALLIS at regional scale for the identified top 3 MAEZ of each AEZ as described in Section 3.2.1. (Tables 15, 16, 19). Afterwards, the MAEZ already covered by existing long-term field trials will be described to provide an overview of which MALLIS are already being investigated under field conditions (Section 4.2.1.). Finally, MALLIS will be developed for the new field trials (field-to-farm scale) to be established by the consortium partners according to those MAEZ where information on field performance is required (4.2.2.). This is done by UHOH for the new field trials to be established in AEZ 2+3 (Fig. 5) and by UNICT for field trials to be performed in AEZ 1 (Fig. 5).

4.1. Industrial crops MALLIS at regional scale

It was found that the industrial crops of all biomass types (lignocellulosic, multipurpose, oil and wood) selected for MAGIC field trials show good growth suitability under the wide range of agro-ecological conditions in Europe (EU-28) (Table 20). Moreover, some crops, e.g. camelina, crambe, tall wheatgrass and miscanthus, can be grown across all three regions (AEZ 1-3), whereas others, such as wild sugarcane, giant reed and castor bean, strongly depend on specific agro-ecological conditions (Figs. 19-37, Tables 20, 21, 23). The proportions of total area per AEZ of the crops range between 0% and 99% (216,577 km²). Overall, the crops potentially suitable for cultivation with the largest area of marginal lands across AEZ 1-3 (within EU-28) are camelina (579,446 km²), tall wheatgrass (534,776 km²), and crambe (522,780 km²). However, the range of crops potentially suitable for cultivation on the various relevant marginal lands identified here is much wider than the crops mentioned above (Tables 24-29). In many cases, there are potentially multiple choices for each of the selected types of biomass (Tables 24-29). Consequently, a site-specific, both user- and environment-oriented crop selection is highly recommended, especially considering aspects of biodiversity conservation, reduced negative externalities etc. (Fig. 2, Boxes 4.1.3 and 4.1.4). This means that those crops with the best growth suitability within a specific region are not necessarily ranked higher in production preference than other crops (rather they form a minimum choice for industrial crop cultivation under the given growth limitations). Instead, all suitable crops should be further evaluated considering both

their MCA value, especially with regard to production costs and marketing potential of their biomass, and their overall ecological impact and contribution to ecosystem functions. In addition, the low-input practices applied on specific sites could further restrict the choice of crops. For example, annual biomass crops such as camelina and crambe are not recommended for a drought-affected region additionally limited by coarse sand (MAEZ: CL_RT_1), if perennial biomass crops (PBC) e.g. miscanthus and switchgrass were also identified as suitable for that region. This is because CL_RT_1 sites are potentially prone to erosion and thus require specific soil protection measures such as no-tillage and reduced weeding, both of which can be provided by PBC cultivation (Chapter 1.1). Furthermore, regions affected by low temperature or excessive wetness (CL, WT) may also be potentially suitable for camelina and crambe, but their oil yield potential is probably very low under these conditions. Instead, for both conditions, the higher yield potential (including a better workability) and better overall ecological performance of miscanthus and other PBC e.g. willow and poplar render them much more suitable for biomass production in such regions..

Most of the identified marginal land could potentially be used for industrial crop cultivation: In AEZ 1 and 2, nearly 100% of total marginal area can be cultivated with at least one of the selected industrial crops (Fig. 18). However, as expected, oil crops are predominant in AEZ 1 and lignocellulosic crops are predominant in AEZ 2 and AEZ 3 MAEZ (Table 20). For some crops, such as camelina, the elaborated suitability values should be carefully interpreted under certain growth season climate conditions, because there may be relevant differences between the crops in the weather conditions they require for both a good yield and quality level (Zubr, 1997; Zanetti et al., 2013). This, and other very crop-specific aspects of yield- and quality-determining parameters, could not be considered for mapping but will be further investigated in MAGIC WP4. Consequently, the mapping resulted in an indication of general growth suitability without providing any information on (i) the achievable yield, and (ii) whether the crops deliver an economic return under these conditions. Production costs are particularly high for annual crops as they need to be newly established every year and well designed crop rotation systems are necessary, which might be difficult in some cases. For example, camelina, crambe and Ethiopian mustard - all members of the plant family Brassicaceae - each require a crop rotation system that does not contain other Brassicaceae to avoid an increase in plant pathogens and pests. Other annual crops not covered by this study (Table 1), such as flax (*Linum* L.) and meadowfoam (*Limnanthes alba* L.), could become relevant for further consideration here. By contrast, PBC have low production costs because they only need to be established once in a plantation lifetime. Another factor to be considered is that PBC react less strongly to adverse climatic conditions than annual crops. Therefore, the production of PBC often provides higher biomass yields and carries a lower production risk than annual crops.

In this study, the suitability ranking was performed on the basis of the field performance observed for existing genotypes of the different industrial crops. For example, all the rankings for miscanthus were provided for the presently only commercially grown genotype *Miscanthus x giganteus*. However, miscanthus breeding programs are currently focusing on the provision of stress-tolerant (drought, salinity, cold) genotypes for marginal land in Europe. In future, this will extend the marginal areas suitable for miscanthus production. Similar developments will become relevant for other industrial crops when appropriate breeding programs are in place.

Another issue not covered by this study is the distribution of the MAEZ and the potential of clustering MAEZ regions. This would be highly relevant if large construction schemes such as industrial facilities or infrastructure measures are planned to be state-subsidized. As shown in Figure 6, there are large regions across Europe where the density of biorefineries is low, even though they are surrounded by marginal land suitable for many industrial crops (compare Figs. 19-37). Clearly, the vicinity of biorefineries would raise the economic attractiveness of biomass production on marginal land and the choice of crops would be steered by the specific demands of the respective biorefinery.

Applying the preliminary results of the multi-criteria analysis (Table 22) to the combined growth suitability results (Figs. 19-37) revealed that it is important to also take the potential crop performance into account for optimal MALLIS development (Table 23). For instance, in some Continental regions (AEZ 3) it could be feasible to grow miscanthus due to its high MCA value (4.9) even though the size of the total suitability area is very low in comparison to the other crops (Table 23). The high MCA value for miscanthus can be attributed to the multiple established material and energetic uses of and increasing demand for its biomass. Likewise, in AEZ 1, it could be more profitable to encourage both industry and breeding incentives for biomass sorghum rather than promoting crambe, even though the latter shows a wider distribution of growth suitability (Table 23).

For MALLIS implementation at regional scale, both environmental threats and social requirements should also be taken into consideration. Marginal lands could be characterized by fragile environments highly susceptible to any type of external disturbance or input. Key measures that improve resilience are thus to be highly recommended. These include the selection of low-demanding industrial crops (reduces the amount of fertilizers and thus the risk of nutrient leaching), the development of heterogeneous landscape concepts (a number of small fields rather than only a few large fields), and the implementation of agricultural diversification measures (crop rotations, wild flower strips) (Altieri et al., 2017). This is in line with the findings of Wagner (2017) "*that a holistic assessment of the environmental performance of perennial crop-based value chains should*

at least include the impact categories marine ecotoxicity, human toxicity, agricultural land occupation, freshwater eutrophication and freshwater ecotoxicity" as well as biodiversity and soil quality, instead of only considering the Global Warming Potential. A more holistic evaluation of the MALLIS implementation would require analysis of the prevailing agricultural system structures and rural community behavior patterns using specific bottom-up research approaches such as the Integrated Renewable Energy Potential Assessment (IREPA) (Winkler et al., 2017). This would take the local diversity and underlying social structures into consideration, which could potentially positively influence the overall public acceptance of the MALLIS (Kiesel et al., 2017).

4.2. Industrial crops MALLIS for new field trials at field-to-farm scale

In the Grant Agreement, new field trials were suggested to be established on the given marginal growth conditions (Table A 3). In this chapter, we aim at approving these concepts according to the developed rankings of both the crop-suitability (including the economic feasibility) and the (other) agricultural practices. During the implementation of the proposal, the consortium partners already identified most relevant biophysical constraints at their field sites and the potentially most suitable crop spiecies to test on field for their specific AEZ conditions (Table A 3). The main agricultural practice categories found to be most relevant for MALLIS development were:

- crop selection (best adapted to site conditions);
- soil tillage (no-tillage vs. reduced tillage);
- fertilization (no fertilization vs. reduced fertilization);
- weed control (no-weeding vs. mechanical control);
- irrigation (no-irrigation vs. reduced irrigation) (only in AEZ-1 (Mediterranean).

Although the low-input practices are a package of practices to minimize off-farm resources, decrease the environmetal pressure and ultimately increase the economy of the cultivation phase, it should be noted that in MAGIC experimental trials are planned which require levels of each treatment as variables of the experiment. Here, we propose both the combination of the practices and the levels of each input to be taken into account for experimental field management. A biomass type-specific protocol providing all instructions required for a successful realization of the measurements and determinations in both field and laboratory work was sent to the consortium partners separately. This protocol was not included to this study.

4.2.1. Existing long-term field trials

Furthermore, the already existing long-term field trials of the MAGIC participants (Table 30) will be considered for the identification of relevant MAEZ either still to be covered or extended by the new field trials. Furthermore, Table 30 shows which MAEZs are covered by the existing long term field trials and which crops are already being cultivated in which AEZ. These field trials will be analyzed regarding their potential to provide information on relevant MAEZ, so that these MAEZ can be considered sufficiently covered and no new field trials are required. The results will be presented in both annual reports and Deliverable 4.6 (Long-term performance of perennial industrial crops grown on marginal land).

Table 30: Overview of MAEZ covered by existing long-term field trials of the consortium partners. The industrial crops which are part of both the pre-selected industrial crops (Table 1) and the long-term field trials are listed per AEZ.

	MAEZ[a]		
Partner[b]	AEZ[c]	Constraints[d]	Crops[e]
AUA	1	CH_C	Cardoon, Giant reed, Hemp, Miscanthus, Switchgras
CRES	1	TX_S, ST, RT, CL_D	
FCT UNL	1	TX_S, CH_C, CL_D	
UNICT	1	FE, TR, CH_S, CL_D	
DLO	2	TX_S, CH_S	Miscanthus, Switchgrass
INRA	2	RT, CH_D, CL_D	
NOVABIOM	2	TX_S, WT, TR, CH_C, CL_D	
3B	3	TX_S	Giant reed, Hemp, Miscanthus, Poplar, Reed canary grass, Switchgrass, Willow
IBC	3	TX_S, TX_C, RT, TR, CH_S	
INF & MP	3	CH_C, CL_L, CL_D	
SILAVA	3	TX_S, WT, CL_D	
UHOH	3	ST, RT, CL_L	

[a] MAEZ = Combination of AEZ and constraint(s).
[b] According to MAGIC Grant agreement.
[c] AEZ = Agro-ecological zone as described according to Figure 5.
[d] CH = Poor chemical properties: Contaminated soils (CH_C) and salinity (CH_S); CL = Adverse climatic conditions: Dryness (CL_D), low temperature (CL_L); FE = Limited soil fertility; RT = Shallow rooting depth; TX = Unfavourable texture: Coarse sand (TX_S), hard clay (TX_C); TR = Steep slope; ST = Stonyness; WT = Excessive soil moisture.
[e] Overview of crops which are part of long-term field trials belonging to the respective AEZ.

4.2.2. MALLIS for new field trials – experimental scale

This Section starts with an overview of industrial crops recommended for new field trials within MAGIC (Table 31) based on the results of the MAEZ-specific growth suitability

rankings (Tables 24-29). Then, basic low-input recommendations for the aforementioned most relevant agricultural practice categories (i) soil tillage, (ii) fertilization, (iii) weeding and (iv) irrigation are provided. Afterwards, the key requirements for the field trial designs are explained (Section 4.2.2.5.).

Table 31: Recommended MALLIS for new field trials within MAGIC.

Partner	AEZ	MAEZ (constraints)	Supposed conversion routes	Recommended industrial crops	Key management issues
CIEMAT	1	RT_1 (unfavourable texture and stoniness)	Lignocellulosic Woody	Tall wheatgrass, Siberian elm	Minimum/no tillage Rainfed
	1	CL_1 (dryness)	Lignocellulosic	Hemp, Tall wheatgrass	Reduced irrigation vs no irrigation
CRES	1	RT_1 (unfavourable texture and stoniness)	Oil Carbohydrate	Crambe, Camelina, Pennycress, Safflower, Biomass Sorghum	Minimum/no tillage Reduced fertilization Reduced irrigation
	1	FE_1 (acidity)	Lignocellulosic	Tall wheatgrass	Minimum/no tillage Reduced fertilization Reduced irrigation
UNICT	1	TR_1 (steep slope)	Oil Lignocellulosic	Camelina, Crambe, Pennycress, Tall wheatgrass, Cardoon, Safflower	Minimum/no tillage Reduced fertilization (incl. compost) Rainfed
	1	CL_1 (dryness)	Oil lignocellulosic	Hemp, Miscanthus, Giant reed, Wild sugarcane	Minimum/no tillage Reduced fertilization (incl. compost) Reduced irrigation/rainfed
	1	CH_1 (salinity)	Oil	Lupin, Ethiopian mustard, Crambe, Cardoon	Optimal fertilization /reduced fertilization (incl. compost), Reduced irrigation/rainfed
INRA	2	CH_2 (contamination)	Lignocellulosic	Miscanthus	Minimum/no tillage Bio-fertilisation
IBC-SB	3	RT_3 (hard clay and limited soil drainage)	Lignocellulosic Woody	Tall wheatgrass, Willow, Hemp, Poplar, Reed canary gras	Minimum/no tillage Reduced fertilization Weed control/reduced weed control
	3	CH_3 (acidity)	Lignocellulosic Woody	Miscanthus, Cardoon, Tall wheatgrass, Flax, Poplar, Willow, Siberian elm	Minimum/no tillage Reduced fertilization Weed control/reduced weed control
	3	CH_3 (contamination: mineral fertilizers, pesticides, herbicides)	Lignocellulosic	Hemp, Miscanthus, Biomass sorghum, Willow	Minimum/no tillage Reduced fertilization Weed control/reduced weed control
SILAVA	3	CL_RT_3 (unfavourable texture and stoniness combined with low temperature)	Woody	Willow, Siberian elm, Poplar	Minimum/no tillage Reduced fertilization
UHOH	3	CL_RT_3 (unfavorable texture and stoniness combined with low temperature)	Lignocellulosic Oil	Camelina, Tall wheatgrass, Reed canary grass, Poplar, Crambe, Willow, Miscanthus, Hemp	Minimum/no tillage Reduced fertilization Weed control/reduced weed control

4.2.2.1. Soil tillage

Tillage strategy is particularly important on sites characterized by biophysical limitations as unfovourable climate (high and low temperature), dryness and excess of soil moisture, poor soil drainage, unfavourable texture and stoniness, steep slope, slallow soil, contaminated and poor chemical properties soil, as shown in table 4ff.

Althought it is difficult to generalize due to the heterogeneity of soils, specific biophysical limitations and crops to grow, in these conditions strategies, such as reduced till or minimum till or no-till are preferred over conventional tillage.

A global meta-analysis demonstrated that no-till resulted in yield declines in tropical latitudes but there are clearly some contexts in which no-till increases yields relative to conventional tillage systems; these are typically in arid regions – particularly where water is limiting to crop growth (Pittelkow et al., 2015). It has been reported that crop grown with no-till has more climate adaptation (e.g. drought and high temperatures) achieving higher yield than those on tilled plots; on the other hand, crops grown on minimum tillage showed higher yields than conventional and no-till due to breaking of compact layer and moderate soil perturbation (Busari et al., 2015).

Although there is a general consensus on reduction of tillage intensity, there is also scientific evidence in favour of promoting conservation agriculture in general rather than no-tillage exclusively.

Conservation tillage (or reduced tillage) is a system that conserves soil, water and energy resources through the reduction of tillage intensity, noninversion of the soil and retention of crop residue. In general, it is any method of soil cultivation that leaves the previous year's crop residue, at least 30% of the soil surface is covered with crop residue/organic residue following planting.

Conservation tillage methods include minimum-till, strip-till, ridge-till, mulch-till and zero-till. This latter is the extreme form of conservation tillage and it is used in large-scale crop cultivation systems because large machines are required for planting. For smaller-scale farms, no adequate machines are available for sowing, although very small scale farmers may do so by hand. In zero-tillage, crops are planted with minimum disturbance to the soil by planting the seeds in an un-ploughed field with no other land preparation. A typical zero-tillage machine is a heavy implement that can sow seed in slits 2-3 cm wide and 4-7 cm deep. Fertilizers are applied in one operation.

Strip-tillage involves tilling the soil only in narrow strips with the rest of the field left untilled. Ridge-till involves planting seeds in the valleys between carefully molded ridges of soil. The previous crop's residue is cleared off ridge-tops into adjacent furrows to make way for the new crop being planted on ridges. Maintaining the ridges is essential and requires modified or specialised equipment.

Mulch-till is another reduced tillage system in which residue is partially incorporated using chisels, sweeps, field cultivators, or similar farming implements that leaves at least one third of the soil surface covered with crop residue.

Minimum tillage is a technique less intensive than conventional tillage and more intensive than zero-till.It can be done by a simple disc harrowing or with a field cultivators, at about 8-15 cm deep. The sowing can be carried out in two different moments or at the same time, thanks to self-propelled machines able to perform, with a single pass, even fertilization, rolling, weeding and other possible practices. Minimum tillage can be also carried out on strips from 5 to 30 cm wide and 15-20 cm deep.

According to the crop and biophysical limitation, the proposed levels for soil tillage (within new field trials) will be: i) zero or no-till with direct sowing (tillage maximum 7 cm deep) done manually due to the small-scale of experiment and ii) reduced or minimum-till by means of field cultivator or disk harrow at 15-20 cm followed by sowing at the desired plant density. Each method has to consider the previous crop residues or the fallow residues left on the ground by at least 30% of the soil surface.

Fertilizers, either organic or mineral, can be applied just before minimum-till or during the sowing in zero-till.

4.2.2.2. Fertilization

For fertilization, the residues have to be taken into account, which were left on the ground from the previous crop or from the fallow in trials involving the soil tillage as experimental variable.

Even in this case, is not simple to give static numbers to apply, as the fertilization can greatly change according to the crop, type of soil, and the environmental conditions. According to the biophysical limitations, fertilization is beneficial in all cases, except in excessive moisture and poor drained soils. In general, organic fertilizers are more beneficial in term of enhancing biophysical properties than mineral ones, however, the release of nutrients is slower.

For an adequate fertilization management, it is important considering the optimal technical dose of each nutrient depending on (i) the nutritional need of the crop, (ii) the amount of non-anthropogenic nutrient input such as atmospheric deposition and the mineralization of soil organic matter of previous residues, and (iii) the amount of nutrient getting lost in the course of leaching, volatilization, denitrification or immobilization. This optimal technical dose can be calculated according to equation (1):

$$Q = F – (P + M + Cp) + (L + V + D + I) \quad (1)$$

Q: amount of nutrient to be distributed with fertilizers;

F: nutritional need of the crop;

P: supply derived from atmospheric precipitation;

M: supply derived from the mineralization of soil organic matter;

Cp: supply derived from the preceding crop;

L: amount lost due to leaching;

V: amount lost due to volatilization;

D: amount lost due to denitrification;

I: amount not available due to nutrient immobilization.

Before to applying fertilizers it is necessary to know the soil chemical-physical properties before the growing season starts. Fertlization levels proposed are:

- 50% of the optimal technical dose for each crop type and soil type, and
- Control (no fertilization).

4.2.2.3. Weeding

Mechanical tilling can remove weeds around crop plants at various points in the growing season.

In the context of conservative agriculture, a possible strategy for no-weeding management could be the false or stale seed bed: it is a weed control technique which involves the

preparation of a seedbed some weeks before the desired crop is sown, in order to allow weed seeds to germinate. For instance, this can be done in early spring, when the weather is still too cold for seed crop germination, or in early autumn (in southern Europe) when the temperatures are still too high for sowing the desired crop. The preparation of false seedbeds ensures that any weed seeds that have been disturbed and brought to the soil surface during soil preparation will thus have a chance to germinate, and can then be hoed off or eliminated by other means.

4.2.2.4. Irrigation

Irrigation practice has been proposed by partners working on AEZ-1 (Mediterranean). The levels of irrigation will be no-irrigation vs. reduced irrigation.

Before to plan an irrigation it is important to know:

Crop species:
Some crops have higher water requirements than others (Table 8).

Crop growth stage:
Crop water requirements vary depending on growth stage. Young plants transpire less than larger plants due to a smaller leaf surface area.

Relative maturity:
Longer season crops will require more water over the growing season than short-season crops.

Weather conditions:
Daily evapotranspiration (ET) is influenced by solar radiation, air temperature, relative humidity, and wind. High air temperatures, low humidity, clear skies, and high wind speed cause a large evaporative demand.

Water holding capacity of the soil:
Fine textured soils hold more water than coarse textured soils. A soil's water holding capacity indicates both amount of water available for plant use and the maximum allowable depletion of the soil water.

Tillage system:
Minimizing soil disturbance from tillage and increasing surface crop residue can reduce soil water evaporation.

The time of irrigation is determined on the basis of the maximum available water content in the soil where roots are expected to expand, and is calculated according to equation (2):

$$V = 0.66\ (FC - WP) \times \Phi \times D \qquad (2)$$

V= water amount in mm;

0.66= fraction of readily available soil water permitting unrestricted evapotranspiration;

FC= soil water at field capacity (% dry soil weight);

WP= soil water at wilting point (% dry soil weight);

Φ= apparent volumetric mass (kg m^{-3});

D= rooting depth, where the bulk of the roots are mainly present (mm)

Irrigation is usually applied when the sum of daily crop evapotranspiration (ETc) corresponds to the water amount to supply (V). The daily ETc is calculated according to equation (3):

$$ETc = ET_0 \times Kp \times Kc \qquad (3)$$

ETc is the maximum daily crop evapotranspiration (mm);

ET_0 is the reference evaporation of class-A pan (mm);

Kp is the pan coefficient (varies according to the environment);

Kc is the crop coefficient (varies with crop and phenological stage).

Thus, the level of irrigation treatment could be the following:

no-irrigation (rainfed);

reduced irrigation (i.e., 50% of the ETc restoration).

4.2.2.5. MALLIS field trial layout

The experimental design for the new field trials will be a split-plot, replicated three times. In the following sections we propose the experimental layout according to the combination of low-input practices (treatments, including the selected crop species) and levels discussed above. The experimental layout is demonstrated step-by-step from one to four factors (× number of crop species), because in some cases (new field trials), maybe only three or less factors could be able to be investigated.

One-factor × crop species

This experimental layout represents a split-plot where the main factor can be the irrigation or soil tillage or fertilization or weed control and the sub-plot the species. Species are randomized, and the replications represent the three blocks. In the figure below the main plot is represented by reduced irrigation (50% of maximum ET restoration) and rainfed conditions, and 5 species as sub-plot.

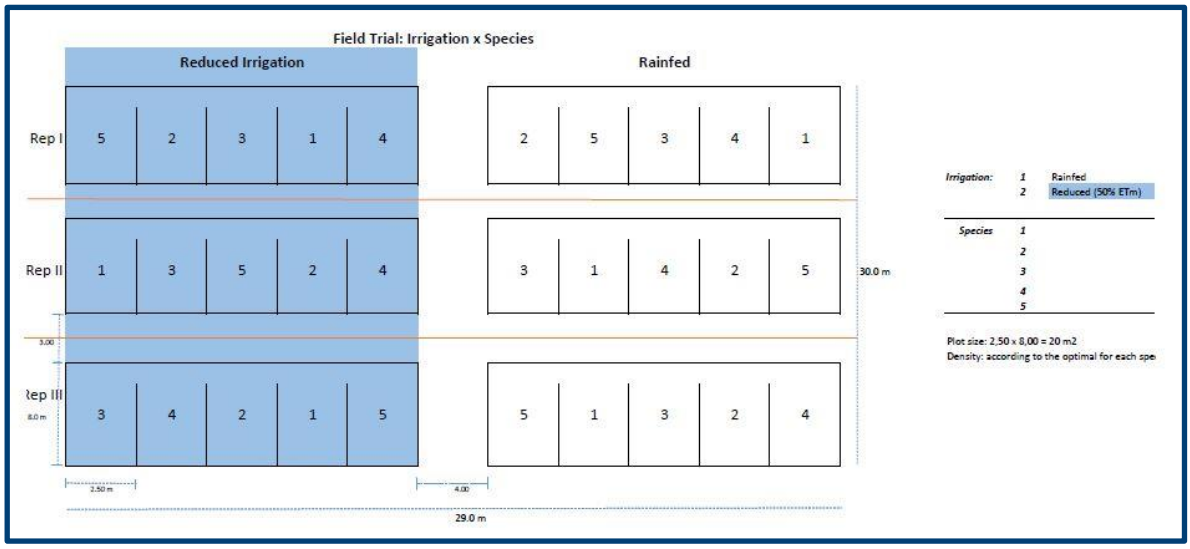

Figure 38: One-factor (irrigation) × species design.

Two-factor × crop species

This experimental layout represents a 2-factor split-plot where species are randomized, and the replications represent the three blocks. In the figure below, the main plot is represented by soil tillage (minimum-till vs no-till), the sub-plot by irrigation (reduced vs rainfed) and 5 species as sub-sub-plot.

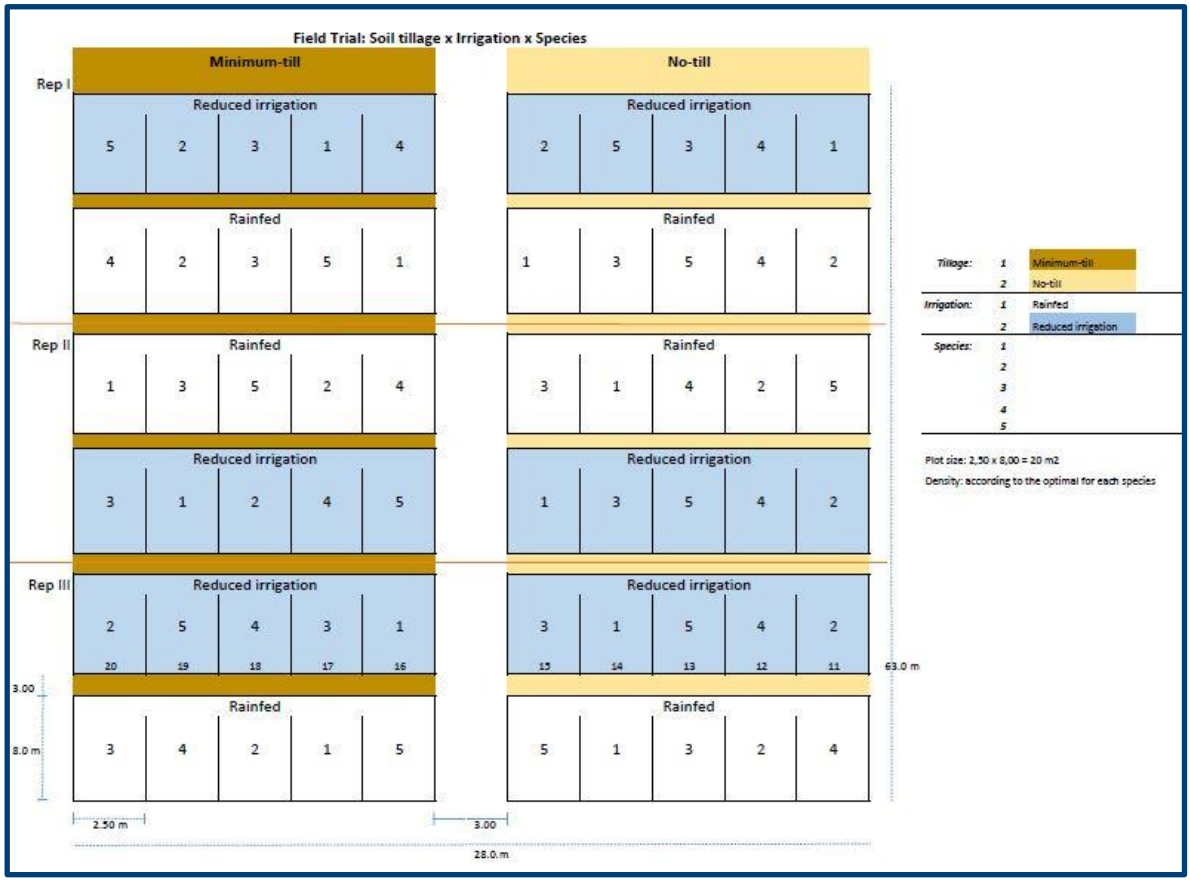

Figure 39: Two-factor (soil tillage and irrigation) × species design.

Three-factor × crop species

This experimental layout represents a 3-factor split-plot where species are randomized, and the replications represent the three blocks. In the figure below the main plot is represented by soil tillage (minimum-till vs no-till), the sub-plot by irrigation (reduced vs rainfed) and the sub-sub-plot by species which are further split in no-fertilization vs reduced fertilization treatment.

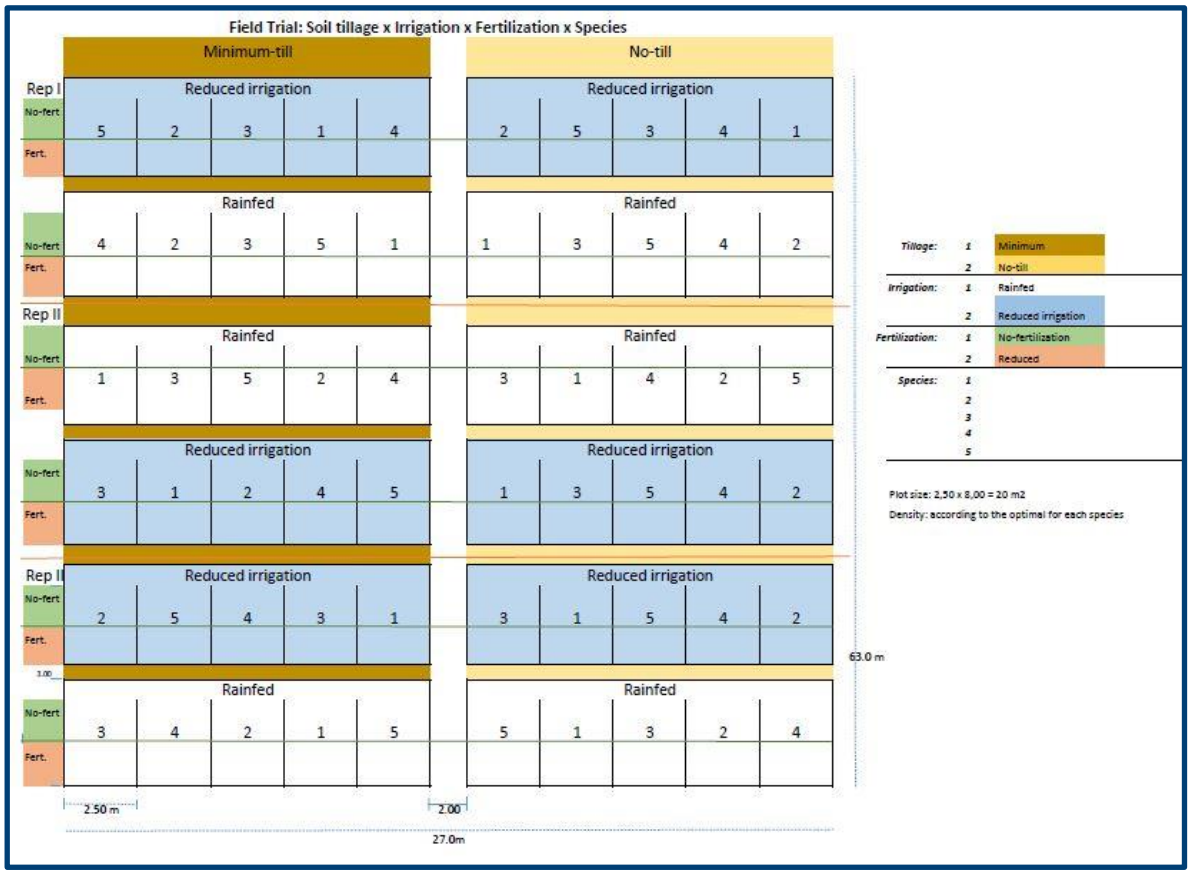

Figure 40: Three-factor (soil tillage, irrigation and fertilization) × species design.

Four-factor × crop species

This experimental layout represents a 4-factor split-plot where species is randomized, and the replications represent the three blocks. In the figure below the main plot is represented by soil tillage (minimum-till vs no-till), the sub-plot by irrigation (reduced vs rainfed), the sub-sub-plot by species which are further split twice in no-fertilization vs reduced fertilization treatment, and no-weeding vs mechanical weeding treatment.

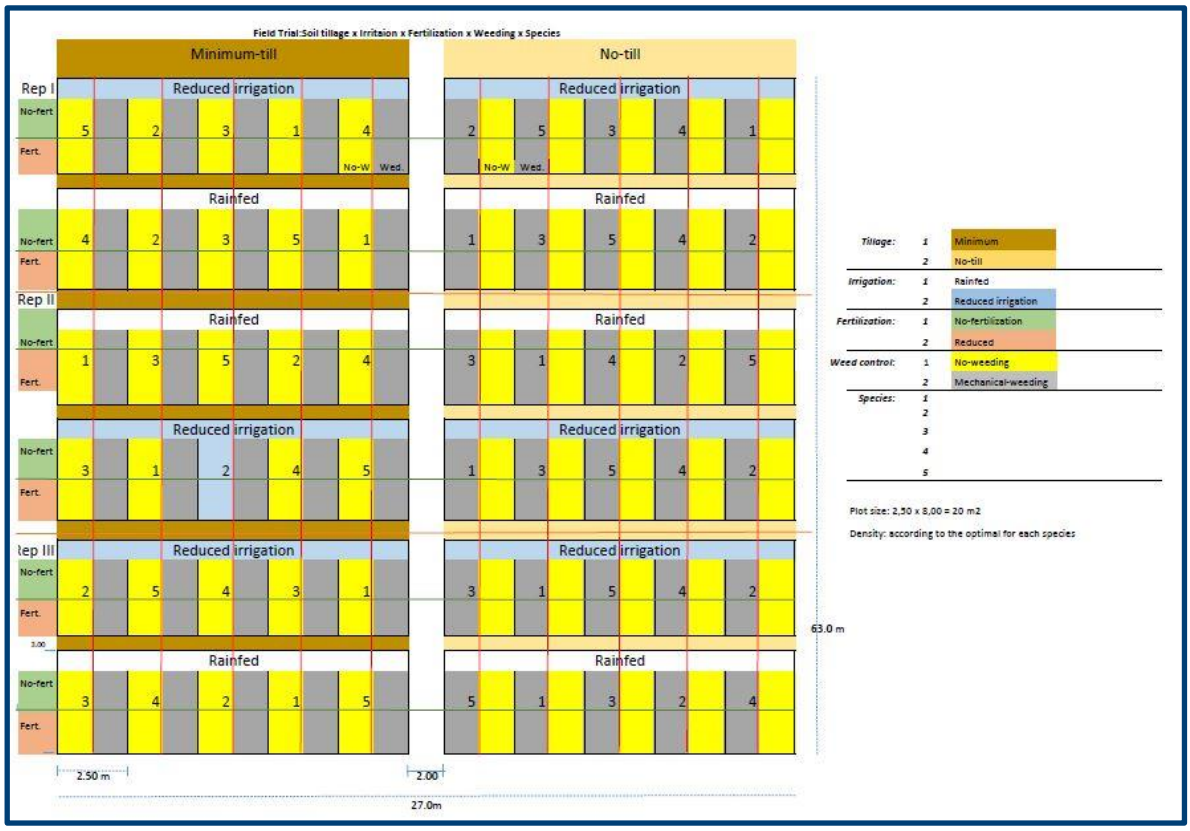

Figure 41: Four-factor (soil tillage, irrigation, fertilization and weed control) × species design.

5. Executive summary

The aim of this study is the development of marginal land low-input systems (MALLIS) for implementation at regional and field-to-farm level in Europe, taking into consideration both economic feasibility and environmental sustainability. The fundamental goal is to support governmental decision-makers in the design of strategies to meet the increasing demand for biomass in a growing bioeconomy.

The development of MALLIS in MAGIC is based on the following definition of low-input agricultural practices: a component of agricultural management systems for sustainable crop production that focuses on achieving high output through the selection of appropriate crop type or development of new varieties appropriate for the prevailing marginality constraints. These practices aim not only to fulfil optimal crop requirements but also to enhance environmental and ecological services and contribute towards the development of farm economy in a specific climatic zone.

The first step was an investigation into the size and distribution of marginal areas in Europe and the reasons for limitations to food crop production on such marginal lands. This was based on the results of WP2 (MAGIC-MAPS) where the prevalent marginal agro-ecological zones (MAEZ) where identified and mapped. A 'MAEZ' is defined here as the combination of a biophysical constraint to crop production (M for marginal) and a climatic zone (AEZ). Table E1 describes the MAEZ identified as most relevant for EU-28 (relative share >1%).

Table E 1: Most relevant (in terms of area) MAEZ (the combinations of AEZ and constraint) identified for different AEZ in Europe (Table 16). Both the relevant potential additional risks per constraint through non-utilization and the overall chances of best practice low-input agricultural utilization are provided.

AEZ	MAEZ code	MAEZ description	Additional risks	Overall chances through implementation of optimized MALLIS
Mediterranean (AEZ 1)	CL_1	Adverse climate - Dryness	Desertification/ salinization	• Avoid HNV[a] farmland loss (biodiversity),
	FE_1	Low soil fertility – low SOC[b]	Loss of SOC, erosion	• Increase biomass
	RT_1	Adverse rooting –shallow soils, stoniness, heavy clay	Erosion, compaction, waterlogging	• Stop land abandonment
	TR_1	Steep slope	Erosion	• Stop population decline
Atlantic (AEZ 2)	RT_2, TX_2	Limitations rooting – soil texture (sandy soils, shallow & organic soils)	Loss SOC, erosion	• Alternative income opportunities
	CL_2	Adverse climate – short growing season	-	
	WT_2	Excessive soil moisture	Loss SOC (peat)	
Continental (AEZ 3)	RT_3, TX_3	Limitations in rooting – organic & sandy soils	Erosion, loss SOC	
	CH_3	Adverse chemical conditions - salinity & sodicity	Salinization, erosion	
	WT_3	Excessive wetness	Loss SOC (peat)	

[a] HNV = High nature value
[b] SOC = Soil organic carbon

The second step was the identification of measures suitable for the alleviation of biophysical constraints (Table E 2, E 2ff). This involved the conduction of a comprehensive literature review of agricultural practices that can potentially overcome individual biophysical constraints. These were then critically assessed by all WP4 participants (experts) of the MAGIC consortium. Thus, the development of MALLIS considered both literature data and expert opinion. The effects of all the identified agricultural practices on the major constraints (i.e. how they help to alleviate growth-limiting conditions) were estimated and summarized in an easy understandable ranking system.

The selection of suitable industrial crops was found to be the most important component in the development of MALLIS, because all other measures (tillage, fertilization, weeding, irrigation etc.) very much depend on the site-specific performance of the crop. In order to reduce the number of potential crops, the results from WP2 (MAGIC-CROPS: pre-selection of most promising industrial crops) were added to the overall crop suitability ranking according to both climatic and geographic conditions of the MAEZ (regional level) and the locations of existing and new field trials (farm level) (Table E 3).

Table E 2: Potential effects (ranking) of structured and systematic agricultural measures on agriculture facing biophysical constraints as selected by expert opinion; (from -3 = strong negative effect to +3 = strong positive effect).

				Biophysical constraints												
				Climatical				Soil / terrain								
Dimension	Category of measure	Method/ Strategy	Technique	Low temperature	High temperature	Dryness	Excessive moisture	Poor soil drainage	Unfav. texture / stoniness	Shallow rooting depth	Steep slope	Low soil fertility	Alkalinity	Acidity	Salinity	Other contamination
Structured measures	Irrigation	Surface irrigation	Line irrigation	-1	0	1	-3	-3	-1	1	-3	1	0	0	1	0
		Pressurized irrigation	Sprinkler irrigation	0	2	2	-3	0	2	1	1	1	1	1	1	0
			Microirrigation (drip irrigation)	0	0	3	-3	1	3	3	2	2	0	0	2	0
			Deficit irrigation technique	0	0	3	-3	1	2	2	3	3	1	1	-1	0
	Landscape management	Field arrangement	Terracing	0	0	0	0	0	0	0	3	0	0	0	0	0
			Field shaping / planting density & geometry	0	0	1	1	0	2	2	1	0	0	0	0	0
		Field surroundings	Hedges	1	0	0	1	1	0	0	1	0	0	0	0	0
			Water channel	-1	0	-3	2	3	0	0	-3	0	1	1	0	0
Systematic measures	Cropping-based measures	Temporal diversification	Catch/ cover crop	1	2	1	2	3	1	-1	0	1	0	0	1	1
			Crop rotation	0	0	1	0	1	2	1	-1	2	0	0	1	2
		Spatial diversification	Agroforestry system	0	0	1	2	2	2	1	3	2	2	2	0	2
			Intercropping	1	1	2	2	2	1	0	2	1	1	1	1	1
			Mixed cropping	1	1	1	2	1	2	0	1	2	1	1	1	1
Crop selection	Morpholo-gical traits	Rooting zone	Deep	1	2	3	2	3	-1	-3	2	1	1	1	1	0
			Shallow	1	0	-3	-1	-2	2	3	1	0	0	0	0	0
	Physiolo-gical traits	Photosynthetic pathway	C3	3	1	0	0	0	0	0	0	0	0	0	0	0
			C4	1	3	2	0	0	0	0	0	0	0	0	1	0
		Life cycle	Annual	0	0	0	-2	-3	0	0	0	1	0	0	1	1
			Biennial	1	1	1	1	1	0	1	1	2	0	0	1	1
			Perennial	2	1	3	2	2	1	2	2	3	1	1	2	1

Table E 2ff: Potential effects (ranking) of management systems on agriculture facing biophysical constraints as selected by expert opinion; (from -3 = strong negative effect to +3 = strong positive effect).

				Biophysical Constraints												
				Climatic				Soil / terrain								
Dimension	Category of measure	Method/ Strategy	Technique	Low temperature	High temperature	Dryness	Excessive moisture	Poor soil drainage	Unfav. texture / stoniness	Shallow rooting depth	Steep slope	Low soil fertility	Alkalinity	Acidity	Salinity	Other contamination
Components of management system	Soil cultivation	Tillage	Full till	1	-2	-2	-3	-1	-1	-1	-3	-1	1	1	0	1
			Reduced till	-1	1	1	1	1	1	1	-1	1	0	0	0	1
			Precision tillage	3	2	2	0	2	2	1	1	2	0	0	0	1
			No till	2	3	3	2	1	2	2	3	2	0	0	0	0
		Mulching	Living mulch	1	-2	-2	3	1	1	-1	2	2	1	1	1	-1
			Cover soil with film	2	1	2	-1	-2	2	1	1	1	0	0	-1	-1
			Harvest residuals	2	-1	-1	0	1	1	-1	-3	2	1	1	0	-1
	Establishment/ planting material	Priming of seeds / planting material	Pesticides	1	0	1	1	2	1	0	0	1	1	1	1	0
			Micronutrients	1	1	1	1	1	2	1	0	3	0	1	1	-1
			Bio-stimulators	0	0	1	1	1	2	1	0	2	1	1	1	0
		Planting technique	Rhizomes	1	1	1	-1	0	1	1	1	1	-1	-1	0	0
			Plantlets	1	2	2	1	1	2	2	2	2	0	0	1	0
			Collars	1	2	2	-1	0	0	-1	1	1	-1	-1	-1	0
			Unrooted cuttings	1	2	0	2	1	0	-1	2	0	1	1	1	0
	Crop protection	Pest management measures	Pesticides	1	1	1	1	-1	0	0	2	1	1	1	1	0
			Biological pest control	1	0	0	2	2	2	0	1	1	0	0	0	0
			Crop rotation strategy	2	1	2	1	2	2	1	1	2	1	1	1	2
		Weeding	Mechanical	1	1	1	-1	0	-1	-1	-3	1	0	-1	-1	0
			Thermal	3	1	1	2	2	2	0	0	2	0	0	-1	0
			Chemical	1	1	1	0	-1	2	1	1	0	0	0	1	0
			Biological	2	1	-1	2	2	1	1	2	1	1	1	1	1
			Cover soil with film	2	1	1	0	0	2	2	2	-2	0	0	0	0
	Fertilization	Application technique	Broadcast	-1	1	1	-1	1	1	0	1	1	0	0	0	0
			Ground level	0	1	1	0	0	1	0	-1	1	0	0	-1	0
			Injection	1	2	1	0	2	0	-1	1	1	0	0	0	0
		Source	Organic fertilizer	2	3	3	-1	-1	2	1	2	3	2	2	2	3
			Liming	1	0	0	1	1	2	0	0	2	-1	3	-2	0
			Chemical fertilizer	1	1	1	-1	1	1	1	-1	3	-1	-1	-2	0
		Form	Solid	2	1	2	1	1	2	0	0	1	0	0	1	0
			Liquid	2	-3	-3	-1	1	1	0	0	1	0	1	0	0
		Time of application	Spring	-1	2	2	1	1	1	0	0	1	0	0	0	0
			Summer	-2	1	2	1	1	1	0	0	1	0	0	0	0
			Autumn	0	0	0	-1	1	0	0	1	-1	0	0	0	0
			Winter	0	0	0	-2	-1	0	0	-1	0	0	0	0	0
		Frequency of applications per year	one	1	-1	-1	1	1	-1	1	1	1	0	0	0	0
			> 1	1	1	1	-1	-1	1	-1	-1	2	0	0	0	0

Table E 3: Growth-suitabilities of the pre-selected industrial crops across MAEZ per AEZ under consideration of both climatic and soil conditions. The expected overall performance of the crops (MCA) is indicated by the preliminary results of the multi-criteria analysis (adapted from WP1, Task 1.3). All values are colorized separately for each category.

Mediterranean (AEZ 1)					Atlantic (AEZ 2)					Continental & Boreal (AEZ 3)				
Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA	Crop	Type	km²	%	MCA
Tall wheatgrass	L	211,255	96	4.5	Tall wheatgrass	L	151,166	79	4.5	Tall wheatgrass	L	172,355	86	4.5
Switchgrass	L	160,238	73	4.6	Reed canary grass	L	124,821	65	4.7	Reed canary grass	L	147,470	74	4.7
Miscanthus	L	130,634	60	4.9	Miscanthus	L	83,820	44	4.9	Miscanthus	L	88,010	44	4.9
Giant reed	L	129,501	59	4.8	Switchgrass	L	19,732	10	4.6	Switchgrass	L	26,628	13	4.6
Wild sugarcane	L	46,768	21	4.4	Giant reed	L	2,459	1	4.8	Giant reed	L	1,173	1	4.8
Reed canary grass	L	45,863	21	4.7	Wild sugarcane	L	252	0	4.4	Wild sugarcane	L	0	0	4.4
Lupin	M	201,888	92	3.4	Hemp	M	80,422	42	4.6	Cardoon	M	83,249	42	4.8
Biomass sorghum	M	193,118	88	4.6	Cardoon	M	71,822	37	4.8	Lupin	M	37,162	19	3.4
Cardoon	M	172,804	79	4.8	Lupin	M	36,790	19	3.4	Hemp	M	17,392	9	4.6
Hemp	M	162,794	74	4.6	Biomass sorghum	M	31,322	16	4.6	Biomass sorghum	M	6,323	3	4.6
Crambe	O	216,577	99	3.3	Camelina	O	186,018	97	4.3	Safflower	O	208,154	104	4.5
Camelina	O	209,761	96	4.3	Crambe	O	175,244	91	3.3	Camelina	O	183,667	92	4.3
Pennycress	O	208,388	95	4.4	Safflower	O	145,382	76	4.5	Crambe	O	130,959	66	3.3
Ethiopian mustard	O	184,988	84	4.5	Pennycress	O	64,812	34	4.4	Pennycress	O	76,465	38	4.4
Castor bean	O	160,990	74	4.8	Ethiopian mustard	O	43,177	23	4.5	Ethiopian mustard	O	10,111	5	4.5
Safflower	O	15,660	7	4.5	Castor bean	O	10,658	6	4.8	Castor bean	O	3,412	2	4.8
Siberian elm	W	179,148	82	4.4	Willow	W	164,191	86	4.3	Poplar	W	150,428	75	4.3
Willow	W	56,880	26	4.3	Poplar	W	159,930	83	4.3	Willow	W	119,536	60	4.3
Poplar	W	48,166	22	4.3	Siberian elm	W	20,611	11	4.4	Siberian elm	W	28,261	14	4.4

The final step was the development of MALLIS (here: the combination of recommended industrial crops and key management issues) for both MAEZ and the new field trials based on the constraint-specific suitability ranking of crops and agricultural practices (Table E4).

Table E 4: Recommended MALLIS for new field trials within MAGIC.

Partner	AEZ	MAEZ (constraints)	Supposed conversion routes	Recommended industrial crops	Key management issues
CIEMAT	1	RT_1 (unfavourable texture and stoniness)	Lignocellulosic Woody	Tall wheatgrass, Siberian elm	Minimum/no tillage Rainfed
	1	CL_1 (dryness)	Lignocellulosic	Hemp, Tall wheatgrass	Reduced irrigation vs no irrigation
CRES	1	RT_1 (unfavourable texture and stoniness)	Oil Carbohydrate	Crambe, Camelina, Pennycress, Safflower, Biomass Sorghum	Minimum/no tillage Reduced fertilization Reduced irrigation
	1	FE_1 (acidity)	Lignocellulosic	Tall wheatgrass	Minimum/no tillage Reduced fertilization Reduced irrigation
UNICT	1	TR_1 (steep slope)	Oil Lignocellulosic	Camelina, Crambe, Pennycress, Tall wheatgrass, Cardoon, Safflower	Minimum/no tillage Reduced fertilization (incl. compost) Rainfed
	1	CL_1 (dryness)	Oil lignocellulosic	Hemp, Miscanthus, Giant reed, Wild sugarcane	Minimum/no tillage Reduced fertilization (incl. compost) Reduced irrigation/rainfed
	1	CH_1 (salinity)	Oil	Lupin, Ethiopian mustard, Crambe, Cardoon	Optimal fertilization /reduced fertilization (incl. compost), Reduced irrigation/rainfed
INRA	2	CH_2 (contamination)	Lignocellulosic	Miscanthus	Minimum/no tillage Bio-fertilisation
IBC-SB	3	RT_3 (hard clay and limited soil drainage)	Lignocellulosic Woody	Tall wheatgrass, Willow, Hemp, Poplar, Reed canary gras	Minimum/no tillage Reduced fertilization Weed control/reduced weed control
	3	CH_3 (acidity)	Lignocellulosic Woody	Miscanthus, Cardoon, Tall wheatgrass, Flax, Poplar, Willow, Siberian elm	Minimum/no tillage Reduced fertilization Weed control/reduced weed control
	3	CH_3 (contamination: mineral fertilizers, pesticides, herbicides)	Lignocellulosic	Hemp, Miscanthus, Biomass sorghum, Willow	Minimum/no tillage Reduced fertilization Weed control/reduced weed control
SILAVA	3	CL_RT_3 (unfavourable texture and stoniness combined with low temperature)	Woody	Willow, Siberian elm, Poplar	Minimum/no tillage Reduced fertilization
UHOH	3	CL_RT_3 (unfavorable texture and stoniness combined with low temperature)	Lignocellulosic Oil	Camelina, Tall wheatgrass, Reed canary grass, Poplar, Crambe, Willow, Miscanthus, Hemp	Minimum/no tillage Reduced fertilization Weed control/reduced weed control

References

Alakukku, L., Weisskopf, P., Chamen, W.C.T., Tijink, F.G.J., van der Linden, J.P., Pires, S., Sommer, C., Spoor, G., 2003. Prevention strategies for field traffic-induced subsoil compaction: a review: Part 1. Machine/soil interactions. Soil Tillage Res., Experiences with the Impact and Prevention of Subsoil Compaction in the European Union 73, 145–160. https://doi.org/10.1016/S0167-1987(03)00107-7

Alekseenko, V. A., 2000. Ecological geochemistry. Logos, Moscow

Altieri, M.A., 2002. Agroecology: the science of natural resource management for poor farmers in marginal environments. Agric. Ecosyst. Environ. 93, 1–24. https://doi.org/10.1016/S0167-8809(02)00085-3

Altieri, M.A., Rosset, P., Thrupp, L.A., 1998. The potential of agroecology to combat hunger in the developing world.

Altieri, M. A., Nicholls, C. I., and Montalba, R. (2017). Technological Approaches to Sustainable Agriculture at a Crossroads: An Agroecological Perspective. Sustainability 9, 349. doi:10.3390/su9030349.

Baldock, D., Beaufoy, G., Bennett, H., Clark, J., 1993. Nature conservation and new directions in the common agricultural policy. IEEP. London.

Baldock, D., Viñas, J.M.S., 2002. Environmental Integration and the CAP: A Report to the European Commision, DG Agriculture. Institute for European Environmental Policy.

Baliuk, S., Medvedev, V., Miroshnichenko, M., Tsapko, Y., 2012a. Environmental state of soils in Ukraine. Ukr. Geogr. J. 2, 38–42.

Baliuk, S., Truskavetskyi, R., Tsapko, Y., 2012b. Chemical amelioration of soils (innovation development concept). Miskdruk, Kharkiv.

Baulcombe, D., Crute, I., Davies, B., Dunwell, J., Gale, M., Jones, J., Pretty, J., Sutherland, W., Toulmin, C., 2009. Reaping the benefits: science and the sustainable intensification of global agriculture. The Royal Society.

Biala, K., Terres, J.-M., Pointereau, P., Paracchini, M.L., 2007. Low Input Farming Systems: an opportunity to develop sustainable agriculture. Proc. JRC Summer Univ. Ranco 2–5.

Bonhomme, R., 2000. Bases and limits to using ‘degree. day’ units. Eur. J. Agron. 13, 1–10.

Breemen, N. van, Mulder, J., Driscoll, C.T., 1983. Acidification and alkalinization of soils. Plant Soil 75, 283–308. https://doi.org/10.1007/BF02369968

Busari, M.A., Kukal, S.S., Kaur, A., Bhatt, R., Dulazi, A.A., 2015. Conservation tillage impacts on soil, crop and the environment. Int. Soil Water Conserv. Res. 3, 119–129.

Carthy, R.M., Löf, M., Gardiner, E.S., 2018. Early root development of poplars (Populus spp.) in relation to moist and saturated soil conditions. Scand. J. For. Res. 33, 125–132. https://doi.org/10.1080/02827581.2017.1338751

Clifton-Brown, J.C., Jones, M.B., 1997. The thermal response of leaf extension rate in genotypes of the C4–grass Miscanthus: an important factor in determining the potential productivity of different genotypes. J. Exp. Bot. 48, 1573–1581.

Cosentino, S.L., Copani, V., Scalici, G., Scordia, D., Testa, G., 2015. Soil erosion mitigation by perennial species under Mediterranean environment. BioEnergy Res. 8, 1538–1547.

Cosentino, S.L., Patanè, C., Sanzone, E., Testa, G., Scordia, D., 2016. Leaf gas exchange, water status and radiation use efficiency of giant reed (Arundo donax L.) in a changing soil nitrogen fertilization and soil water availability in a semi-arid Mediterranean area. Eur. J. Agron. 72, 56–69.

Cosentino, S.L., Scordia, D., Sanzone, E., Testa, G., Copani, V., 2014. Response of giant reed (Arundo donax L.) to nitrogen fertilization and soil water availability in semi-arid Mediterranean environment. Eur. J. Agron. 60, 22–32.

Elbersen, B., Van Eupen, M., Verzandvoort, S., Boogaard, H., Mucher, S., Cicarreli, T., Elbersen, W., Mantel, S., Bai, Z., MCallum, I., Iqbal, Y., Lewandowski, I., Von Cossel, M., Carrasco, J., Ramos, C.C., Sanz, M., Ciria Ciria, P., Monti, A., Consentoni, S., Scordia, D., Eleftheriadis, I., 2018a. Methodological approaches to identify and map marginal land suitable for industrial crops in Europe (EU deliverable-not published yet) (No. 2.6). WUR, Wageningen, Netherlands.

Elbersen, B., Van Verzandvoort, M., Boogaard, S., Mucher, S., Cicarelli, T., Elbersen, W., Mantel, S., Bai, Z., MCallum, I., Iqbal, Y., Lewandowski, I., Von Cossel, M., Carrasco, J., Ramos, C.C., Sanz, M., Ciria, P., Monti, A., Consentino, S., Scordia, D., Eleftheriadis, I., 2018b. Definition and classification of marginal lands suitable for industrial crops in Europe (EU deliverable-not published yet) (No. 2.1). WUR, Wageningen, Netherlands.

Evgrashkina, G., 2003. The effect of the mining industry on the hydrogeological and soil-ameliorative conditions of the territories.

FAO, 2018. FAO:AG:Conservation agriculture [WWW Document]. URL http://www.fao.org/ag/ca/1a.html (accessed 2.2.18).

FAO, 2007. Ecocrop [WWW Document]. Ecocrop. URL http://ecocrop.fao.org/ecocrop/srv/en/cropSearchForm (accessed 2.2.18).

Fleenor, R. A., 2011. Plant Guide for Camelina (Camelina sativa). USDA-Natural Resources Conservation Service. Spokane, WA 99201. URL https://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwjGla27xa_aAhUQ-6QKHT1-DnUQFggqMAA&url=https%3A%2F%2Fplants.usda.gov%2Fplantguide%2Fpdf%2Fpg_casa2.pdf&usg=AOvVaw0w9hNc3wx87FPrXWabZ0i1

Flexas, J., DIAZ-ESPEJO, A., GalmES, J., Kaldenhoff, R., Medrano, H., RIBAS-CARBO, M., 2007. Rapid variations of mesophyll conductance in response to changes in CO2 concentration around leaves. Plant Cell Environ. 30, 1284–1298.

Fraisse, C. W., Sudduth, K. A., Kitchen, N. R., 2001. Delineation of Site-Specific Management Zones by Unsupervised Classification of Topographic Attributes and Soil Electrical Conductivity. Trans. ASAE 44, 155–166. https://doi.org/10.13031/2013.2296

German Bioeconomy Council, 2015. What is Bioeconomy? [WWW Document]. URL http://biooekonomierat.de/en/bioeconomy/ (accessed 1.18.18).

Godfray, H.C.J., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Nisbett, N., Pretty, J., Robinson, S., Toulmin, C., Whiteley, R., 2010. The future of the global food system. Philos. Trans. R. Soc. Lond. B Biol. Sci. 365, 2769–2777. https://doi.org/10.1098/rstb.2010.0180

Greenland, D.J., 1977. Soil damage by intensive arable cultivation: temporary or permanent? Phil Trans R Soc Lond B 281, 193–208. https://doi.org/10.1098/rstb.1977.0133

Grigoryuk, Y., Tkachev, V., Savinskiy, S., Mushenko, N., Petrenko, N., Shvedova, O., 1999. Research methods and methods for assessing plant resistance to drought and high temperature. Znannia, Kiev.
Gualtieri, G., Bisseling, T., 2000. The evolution of nodulation, in: Plant Molecular Evolution. Springer, Dordrecht, pp. 181–194. https://doi.org/10.1007/978-94-011-4221-2_9
Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H., Hörren, T., 2017. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. PLoS ONE 12(10): e0185809. https://doi.org/10.1371/journal.pone.0185809.
Haynes, R.J., Naidu, R., 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. Nutr. Cycl. Agroecosystems 51, 123–137. https://doi.org/10.1023/A:1009738307837
Hergert, G.W., Nordquist, P.T., Petersen, J.L., Skates, B.A., 1996. Fertilizer and crop management practices for improving maize yields on high pH soils. J. Plant Nutr. 19, 1223–1233. https://doi.org/10.1080/01904169609365193
Hinsinger, P., Plassard, C., Tang, C., Jaillard, B., 2003. Origins of root-mediated pH changes in the rhizosphere and their responses to environmental constraints: A review. Plant Soil 248, 43–59. https://doi.org/10.1023/A:1022371130939
Hodges, T., 1990. Predicting crop phenology. Crc Press.
Horn, R., Domżżał, H., Słowińska-Jurkiewicz, A., van Ouwerkerk, C., 1995. Soil compaction processes and their effects on the structure of arable soils and the environment. Soil Tillage Res., Soil Compaction and the Environment 35, 23–36. https://doi.org/10.1016/0167-1987(95)00479-C
Isbell, F., Adler, P.R., Eisenhauer, N., Fornara, D., Kimmel, K., Kremen, C., Letourneau, D.K., Liebman, M., Polley, H.W., Quijas, S., 2017. Benefits of increasing plant diversity in sustainable agroecosystems. J. Ecol. 105, 871–879.
IUSS Working Group WRB, 2006. World reference base for soil resources (No. 103). FAO, Rome.
Jing, Q., Conijn, S.J.G., Jongschaap, R.E.E., Bindraban, P.S., 2012. Modeling the productivity of energy crops in different agro-ecological environments. Biomass Bioenergy, International Conference on Lignocellulosic ethanol 46, 618–633. https://doi.org/10.1016/j.biombioe.2012.06.035
JRC MARS Explorer, 2018. Weather monitoring maps [WWW Document]. MARS Explor. URL http://193.204.199.189/en/web/mars-explorer/weather-maps (accessed 2.25.18).
Kazakov, Y., Hrystova, T., Kazakova, S., 2000. Drought tolerance of plants and the problem of its study. Issues Biol. Ecol. 5, 3–12.
Kharchenko, S., Pidlisniuk, V., Erickson, L., Stefanovsla, T., 2013. Implementation of sustainable land management when using Miscanthus x giganteus for phytoremediation of soils contaminated by heavy metals, in: CASEE Conference. Presented at the Food and Biomass Production as a Basis for a Sustainable Rural Development, Zagreb, Croatia.
Kiesel, A., Wagner, M., Lewandowski, I., 2017. Environmental Performance of Miscanthus, Switchgrass and Maize: Can C4 Perennials Increase the Sustainability of Biogas Production? Sustainability *9*(1) 5. https://doi.org/10.3390/su9010005

Lawlor, D.W., Cornic, G., 2002. Photosynthetic carbon assimilation and associated metabolism in relation to water deficits in higher plants. Plant Cell Environ. 25, 275–294.
Lewandowski, I., 2016. The Role of Perennial Biomass Crops in a Growing Bioeconomy, in: Perennial Biomass Crops for a Resource-Constrained World. Springer International Publishing AG, Cham, pp. 3–13.
Lewandowski, I., Clifton-Brown, J., Trindade, L.M., Van Der Linden, G., Schwarz, K.-U., Müller-Sämann, K., Anisimov, A., Chen, C.-L., Dolstra, O., Donnison, I.S., 2016. Progress on optimizing miscanthus biomass production for the European bioeconomy: Results of the EU FP7 project OPTIMISC. Front. Plant Sci. 7, 1620.
Lewandowski, I., Lippe, M., Castro-Montoya, J., Dickhöfer, U., Langenberger, G., Pucher, J., Schließmann, U., Derwenskus, F., Schmid-Staiger, U., Lippert, C., 2018. Primary Production, in: Bioeconomy. Springer, Cham, pp. 95–175. https://doi.org/10.1007/978-3-319-68152-8_6
Liu, Xinchao, Dong, Y., Qi, Y., Peng, Q., He, Y., Sun, L., Jia, J., Guo, S., Cao, C., Yan, Z., Liu, Xuehua, 2015. Response of N2O emission to water and nitrogen addition in temperate typical steppe soil in Inner Mongolia, China. Soil Tillage Res. 151, 9–17. https://doi.org/10.1016/j.still.2015.01.008
Lucas, R.E., Davis, J., 1961. Relationships between pH values of organic soils and availabilities of 12 plant nutrients. Soil Sci. 92, 177–182.
Mantel, S., Kauffman, J.., 1995. Agricultural suitability of reference soils (The automated land evaluation system applied to ISRIC soil information system).
Mazur, G., 2008. Reproduction and fertility regulation of light soils, Agrarian science. Kiev.
Medvedev, V., 2009. Soil structure as an ecological factor. Bull. Kharkiv Natl. Agric. Univ. 3, 25–31.
Metzger, M.J., Bunce, R.G.H., Jongman, R.H., Mücher, C.A., Watkins, J.W., 2005. A climatic stratification of the environment of Europe. Glob. Ecol. Biogeogr. 14, 549–563.
Montanarella, L., Tóth, G., 2008. Desertification in Europe, in: 15th International Congress of the International Soil Conservation (ISCO Congress) Soil and Water Conservation, Climate Change and Environmental Sensitivity. Citeseer.
Nadtochii, P., Myslyva, T., Volvach, F., 2010. Soil Ecology. Zhytomyr.
National report on the state of technogenic and natural safety in Ukraine, 2010. National report on the state of technogenic and natural safety in Ukraine.
Nicholls, C.I., Altieri, M.A., 2013. Plant biodiversity enhances bees and other insect pollinators in agroecosystems. A review. Agron. Sustain. Dev. 33, 257–274. https://doi.org/10.1007/s13593-012-0092-y
Norman, D., Janke, R., Freyenberger, S., Schurle, B, Kok, H, 1997. Defining and Implementing Sustainable Agriculture (Kansas Sustainable Agriculture Series, Paper #1; Manhattan KS: Kansas Agricultural Experiment Station
Novikova, A., 2009. Studies of saline and sodic soils: genesis, amelioration, and ecology. Institute for Soil Science and Agrochemistry n.a. Sokolovskyi, Kharkiv.
Novikova, A., 2004. Saline soils: distribution in the world, cultivation, and ecology. Kharkiv National Agricultural University, Kharkiv.

Obenauf, U., Borchardt, I., Lubkowitz, C., Kock, C., 2014. N-Sensor im praktischen Einsatz - Erfahrungen und Ergebnisse aus dem Projekt On Farm Research. https://doi.org/10.5073/JfK.2014.02.03

Panagos, P., Van Liedekerke, M., Jones, A., Montanarella, L., 2012. European Soil Data Centre: Response to European policy support and public data requirements. Land Use Policy 29, 329–338. https://doi.org/10.1016/j.landusepol.2011.07.003

Parr, J.F., Papendick, R.I., Youngberg, I.G., Meyer, R.E., 1990. Sustainable agriculture in the United States. Sustain. Agric. Syst. 50–67.

Peterson, J.C., 1982. Effects of pH upon nutrient availability in a commercial soilless root medium utilized for floral crop production. Ohio State Univ. Ohio Reseach Develoment Cent. Cir 268, 16–19.

Pettinger, N.A., 1935. A useful chart for teaching the relation of soil reaction to the availability of plant nutrients to crops. Virginia Agricultural and Mechanical College and Polytechnic Institute.

Pittelkow, C.M., Linquist, B.A., Lundy, M.E., Liang, X., Van Groenigen, K.J., Lee, J., Van Gestel, N., Six, J., Venterea, R.T., Van Kessel, C., 2015. When does no-till yield more? A global meta-analysis. Field Crops Res. 183, 156–168.

Plisko, I., 2004. Effect of fertilizers, tillage, and agrophysical characteristics of chernozem on crop yield. Bull. Kharkiv Natl. Agric. Univ. 6, 251–256.

Pointereau, P., Bochu, J., Doublet, S., 2012. Characterization and elements for a definition and an analysis of low input farming system in EU-27. Presented at the 10th European IFSA Symposium. SOLAGRO.

Poliovyi, V., 2007. Optimization of fertilization systems in modern agriculture. Volyn, Rivne.

Popescu, A., Alecu, I.N., Dinu, T.A., Stoian, E., Condei, R., Ciocan, H., 2016. Farm Structure and Land Concentration in Romania and the European Union's Agriculture. Agric. Agric. Sci. Procedia, 5th International Conference "Agriculture for Life, Life for Agriculture" 10, 566–577. https://doi.org/10.1016/j.aaspro.2016.09.036

Porter, J.R., Semenov, M.A., 2005. Crop responses to climatic variation. Philos. Trans. R. Soc. B Biol. Sci. 360, 2021–2035.

Potts, S.G., Imperatriz-Fonseca, V.L., Ngo, H.T., Biesmeijer, J.C., Breeze, T.D., Dicks, L.V., Garibaldi, L.A., Hill, R., Settele, J., Vanbergen, A.J., 2016. Summary for policymakers of the assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production.

Pretty, J., 2008. Agricultural sustainability: concepts, principles and evidence. Philos. Trans. R. Soc. B Biol. Sci. 363, 447–465. https://doi.org/10.1098/rstb.2007.2163

Pretty, J., Bharucha, Z.P., 2014. Sustainable intensification in agricultural systems. Ann. Bot. 114, 1571–1596. https://doi.org/10.1093/aob/mcu205

Pretty, J., Toulmin, C., Williams, S., 2011. Sustainable intensification in African agriculture. Int. J. Agric. Sustain. 9, 5–24.

Pyurko, O., Musiienko, M., Hrystova, T., 2000. The problem of halophytism and methods to study, in: Proceedings of int. conf. Proceedings of the Int. Conf. "Problems of modern ecology." Presented at the Problems of modern ecology, Zaporizhzhia.

Ramirez-Almeyda, J., Elbersen, B., Monti, A., Staritsky, I., Panoutsou, C., Alexopoulou, E., Schrijver, R., Elbersen, W., 2017. Assessing the Potentials

for Nonfood Crops, in: Modeling and Optimization of Biomass Supply Chains. Elsevier, pp. 219–251.
Raznopolov, O., Pyurko, O., 2000. Ecological and physiological features of the halophytic vegetation in the Azov Sea region, in: Proceedings of the Int. Conf. “Problems of Modern Ecology.” Presented at the Problems of modern ecology, Zaporizhzhia.
Reckleben, Y., 2014. Sensoren für die Stickstoffdüngung - Erfahrungen in 12 Jahren praktischem Einsatz. https://doi.org/10.5073/JfK.2014.02.02
Reynolds, W.D., Bowman, B.T., Drury, C.F., Tan, C.S., Lu, X., 2002. Indicators of good soil physical quality: density and storage parameters. Geoderma 110, 131–146. https://doi.org/10.1016/S0016-7061(02)00228-8
Romashhenko, M., Baliuk, S., 2000. Irrigation in Ukraine: state and ways of improvement. Svit, Kiev.
Sage, R.F., Sage, T.L., 2013. C4 Plants, in: Levin, S.A. (Ed.), Encyclopedia of Biodiversity (Second Edition). Academic Press, Waltham, pp. 361–381.
Sage, R.F., Sage, T.L., Kocacinar, F., 2012. Photorespiration and the evolution of C4 photosynthesis. Annu. Rev. Plant Biol. 63, 19–47.
Sánchez, E., Scordia, D., Lino, G., Arias, C., Cosentino, S.L., Nogués, S., 2015. Salinity and water stress effects on biomass production in different Arundo donax L. clones. BioEnergy Res. 8, 1461–1479.
Scarlat, N., Dallemand, J.-F., Monforti-Ferrario, F., Nita, V., 2015. The role of biomass and bioenergy in a future bioeconomy: policies and facts. Environ. Dev. 15, 3–34.
Schäfer-Landefeld, L., Brandhuber, R., Fenner, S., Koch, H.-J., Stockfisch, N., 2004. Effects of agricultural machinery with high axle load on soil properties of normally managed fields. Soil Tillage Res. 75, 75–86. https://doi.org/10.1016/S0167-1987(03)00154-5
Schulte, R.P.O., Creamer, R.E., Donnellan, T., Farrelly, N., Fealy, R., O’Donoghue, C., O’hUallachain, D., 2014. Functional land management: A framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. Environ. Sci. Policy 38, 45–58. https://doi.org/10.1016/j.envsci.2013.10.002
Shykula, M., Gnatenko, O., Petrenko, L., Kapshtyk, M., 2004. Soil Protection. Znannia, Kiev.
Smirnov, V., 2007. Effect of geotopological parameters on the landscape-ecological properties of a territory. Bull. Geoecologists’ Soc. Simferopol 9, 13–16.
Smirny, N., Zubova, L., Zubov, A., 2006. Environmental safety of landfills of Donbass landscape.
Smith, K.A., Thomson, P.E., Clayton, H., Mctaggart, I.P., Conen, F., 1998. Effects of temperature, water content and nitrogen fertilisation on emissions of nitrous oxide by soils. Atmos. Environ. 32, 3301–3309. https://doi.org/10.1016/S1352-2310(97)00492-5
Snyder, C.S., Bruulsema, T.W., Jensen, T.L., Fixen, P.E., 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric. Ecosyst. Environ., Reactive nitrogen in agroecosystems: Integration with greenhouse gas interactions 133, 247–266. https://doi.org/10.1016/j.agee.2009.04.021
Spies, C.D., Harms, C.L., 1988. Soil acidity and liming of Indiana soils. Purdue Ext. Publ. AY-267-W.

Staffas, L., Gustavsson, M., McCormick, K., 2013. Strategies and Policies for the Bioeconomy and Bio-Based Economy: An Analysis of Official National Approaches. Sustainability 5, 2751–2769. https://doi.org/10.3390/su5062751

Svetlichnyi, A., Chernyi, S., Shvebs, G., 2004. Erosiology: theoretical and applied aspects. Universytetska Knyha, Sumy.

Terres, J.-M., Hagyo, A., Wania, A., Confalonieri, R., Jones, R., van Diepen, K., Van Orshoven, J., 2014. Scientific contribution on combining biophysical criteria underpinning the delineation of agricultural areas affected by specific constraints: Methodology and factsheets for plausible criteria combinations.

Thomasson, A.J., Jones, R.J.A., 1989. Land evaluation at regional scale, in: Land Qualities in Space and Time, Proceedings of a Symposium Organized by the International Society of Soil Science (ISSS). Pudoc, Wageningen, Netherlands, pp. 231–240.

Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., 2009. Beneficial biofuels—the food, energy, and environment trilemma. Science 325, 270–271.

Tóth, G., Montanarella, L., Rusco, E., 2008. Threats to soil quality in Europe. JRC Scientific and Technical Reports EUR 23438 EN. European Commission Joint Research Centre Institute for Environment and Sustainability, Ispra, Italy.

Tyshhenko, O., Tyshhenko, A., Chernychenko, M., 2013. About the salt resistance of alfalfa and the ways to increase it. Collect. Sci. Pap. “Irrigated Agric. 59, 105–107.

Uphoff, N.T., Altieri, M.A., 1999. Alternatives to conventional modern agriculture for meeting world needs in the next century: report of a Conference on Sustainable Agriculture, Evaluation of New Paradigms and Old Practices, April 26-30, 1999, Bellagio, Italy. Cornell International Institute for Food, Agriculture and Development.

Van Dam, J., Faaij, A.P., Hilbert, J., Petruzzi, H., Turkenburg, W.C., 2009. Large-scale bioenergy production from soybeans and switchgrass in Argentina: Part B. Environmental and socio-economic impacts on a regional level. Renew. Sustain. Energy Rev. 13, 1679–1709.

Van Orshoven, J., Terres, J.-M., Tóth, T., Jones, R., Le-Bas, C., Nachtergaele, F., Rossiter, D., Schulte, R., Van Velthuizen, H., 2014. Updated common bio-physical criteria to define natural constraints for agriculture in Europe - Definition and scientific justification for the common biophysical criteria. JRC Science and Policy Reports. https://doi.org/10.2788/79958

Van Orshoven, J., Terres, J.-M., Tóth, T., Jones, R., Le-Bas, C., Nachtergaele, F., Rossiter, D., Schulte, R., Van Velthuizen, H., 2012. Updated common bio-physical criteria to define natural constraints for agriculture in Europe. JRC Sci. Tech. Rep. Eur. Comm. Jt. Res. Cent. Inst. Environ. Sustain.-IES Luxembg. Available Online Httpmembers Iif Hutot3700abstrJVOJMTTT2012 Pdf. https://doi.org/10.2788/91182

Veremeinko, S., Poliovyi, V., Trusheva, S., 2013. Changes in the composition and properties of sod-podzolic soils of Ukrainian Polissia under the effect of long-term agricultural use. NUWMNRU, Rivne.

Von Cossel, M., Lewandowski, I., 2016. Perennial wild plant mixtures for biomass production: Impact of species composition dynamics on yield performance

over a five-year cultivation period in southwest Germany. Eur. J. Agron. 79, 74–89. https://doi.org/10.1016/j.eja.2016.05.006

Von Cossel, M., Möhring, J., Kiesel, A., Lewandowski, I., 2017. Methane yield performance of amaranth (Amaranthus hypochondriacus L.) and its suitability for legume intercropping in comparison to maize (Zea mays L.). Ind. Crops Prod. 103, 107–121. Doi: 10.1016/j.indcrop.2017.03.047.

Wagner, M., 2017: Methodological approaches for assessing the environmental performance of perennial crop-based value chains. Dissertation. University of Hohenheim. http://opus.uni-hohenheim.de/volltexte/2018/1433/.

Wezel, A., Soboksa, G., McClelland, S., Delespesse, F., Boissau, A., 2015. The blurred boundaries of ecological, sustainable, and agroecological intensification: a review. Agron. Sustain. Dev. 35, 1283–1295.

Winkler, B., Lemke, S., Ritter, J., Lewandowski, I., 2017. Integrated assessment of renewable energy potential: Approach and application in rural South Africa. Environmental Innovation and Societal Transitions 24: 17-31. https://doi.org/10.1016/j.eist.2016.10.002.

Zanetti, F., Monti, A., Marisol, T.B., 2013. Challenges and opportunities for new industrial oilseed crops in EU-27: A review. Industrial Crops and Products 50: 580-595. https://doi.org/10.1016/j.indcrop.2013.08.030.

Zinchuk, P., Zinchuk, M., 2006. The environmental condition of the Volyn region in connection with the current trends in agriculture. Sci. Pap. Volyn Natl. Univ. Protection of the nature of Western Polissia and neighbour territories, 124–130.

Zubr, J., 1997. Oil-seed crop: Camelina sativa. Industrial Crops and Products 6: 113-119. https://doi.org/10.1016/S0926-6690(96)00203-8.

Zucca, C., Biancalani, R., Kapur, S., Akça, E., Zdruli, P., Montanarella, L., Nachtergaele, F., 2014. The Role of Soil Information in Land Degradation and Desertification Mapping: A Review, in: Soil Security for Ecosystem Management, SpringerBriefs in Environment, Security, Development and Peace. Springer, Cham, pp. 31–59. https://doi.org/10.1007/978-3-319-00699-4_3

Annex

Table A 1: Overview of crop-specific data as provided within the Grant Agreement of MAGIC. Here, only the pre-selected industrial crops (MAGIC-CROPS) are shown.

Name (common & Latin) and family	Origin	Where can be grown in Europe	References about its suitability to be grown on marginal lands	Category	Products and markets
Biomass sorghum	Northern Africa	South (S), Central (C)	High drought resistant crop, deep rooting system, can be grown on toxic soils. Currently, is being investigated in BeCool project (www.becoolproject.eu). Recently, had been evaluated in Sweetfuel project (www.sweetfuel-project.eu).	Carbohydrate, Lignocellulosic (annual)	Bioethanol production (1st generation and advanced biofuels), biogas production, animal feed, human feed. Fiber sorghum is a great fiber source.
Camelina	Southern Europe	South (S), Central (C), North (N)	In ITAKA project (www.itaka-project.eu), it had been cultivated on *marginal lands* in Spain for aviation biofuels. Currently, in COSMOS project (http://cosmos-h2020.eu) the best cultural practices in several sites in EU are being investigated. It exists both winter and spring varieties, winter camelina can resist up to -20°C.	Oilseed (annual)	Its oil seeds characterized by high content of erucic acid). Its oil has a large variety of high-added value bioproducts (chemical industry). The cake of the seeds has high protein content and is a valuable source for animal feeding.
Cardoon	South Europe (perennial 5-10 years; established by seeds)	South (S)	Drought resistant crop can be cultivated on arid marginal areas of south EU with the most recent example FIRST2RUN project (www.first2run.eu; BBI project, Flagship) and OPTIMA (FP7 project).	Oilseed/Lignocellulosic/Multipurpose	From its seeds: oil, protein flour, active molecules. From its stems: solid biofuels (energy), paper and pulp, other chemicals, etc. From its roots: organic substances, chemicals, etc.
Castor bean	Mediterranean area	South (S)	It cannot tolerate low temperatures. It can be grown on *marginal lands* (grows best on moderately fertile), which are not competitive with food (economic viable solution for non-productive lands). It can tolerate pH 5.5-6.5 and saline soils.	Oilseed (annual or perennial)	Source of ricin oleic acid, several chemical and medicinal applications. Its oil has international market with more than 700 uses. Castor cake can be used as nematicide
Crambe	Eastern Africa domesticated in Mediterranean	South (S), Central (C), North (N)	Relatively drought tolerant, it tolerates soil pH from 5.0 to 7.8. It can be adapted to marginal land areas with mild winters as an autumn crop, or as a spring one in short season environments. Currently, in COSMOS project (http://cosmos-h2020.eu) the best cultural practices in several sites in EU are being investigated.	Oilseed (annual)	Its oil has high erucic acid and has several industrial applications, while the seed cake can be used for soil bio fumigation.

Name (common & Latin) and family	Origin	Where can be grown in Europe	References about its suitability to be grown on marginal lands	Category	Products and markets
Ethiopian mustard	Native of Africa (Ethiopia)	South (S)	It is considered *drought tolerance crop*. Soils with pH 5.5-8.0. It had been tested in FAIR981946 project (1998-2001).	Oilseed (annual)	Its oil has high erucic acid and has several industrial applications, while the seed cake can be used for soil bio fumigation.
Giant reed	Mediterranean area	South (S)	It has been selected by OPTIMA project (www.optimafp7.eu) as a promising crop to be grown on marginal lands.	Lignocellulosic (perennial with lifespan 10-20 years).	Solid biofuels, advanced biofuels, other industrial applications.
Industrial hemp	Central Asia	South (S), Central (C), North (N)	Currently has been selected by GRACE project (BBI, Demo) as industrial crop for marginal lands. It had been investigated in MULTIHEMP project (http://multihemp.eu). In Poland had been used for soil reclamation.	Oilseed/Fiber crop/Multipurpose (annual)	Multipurpose crop, from its stems (fibers, paper and pulp, building materials, insulation mats, etc.), from its seeds (oil, seeds…)
Lupin	Native of Andean region of Ecuador, Peru and Bolivia.	South (S), Central (C)	It has been selected by LIBBIO project as an industrial crop that can be grown on marginal lands (www.libbio.net). It tolerates the acid soils and it is considered drought tolerance.	Oilseed/Multipurpose	Oil (20%) and protein (40%) can be obtained from lupin seeds.
Miscanthus	Native of Asia	South (S), Central (C), North (N)	It has been selected by OPTIMA (www.optima.fp7.eu) and OPTIMISC (https://optimisc.uni-hohenheim.de/en) projects as a promising crop to be grown on *marginal lands*. Currently, has been included in GRACE project (BBI, Demo) to be grown on marginal lands and/or contaminated lands.	Lignocellulosic (perennial with lifespan 10-20 years).	Solid biofuels, advanced biofuels, other industrial applications
Pennycress	Native to temperate regions of Eurasia	South (S), Central (C), North (N)	It has a short growing cycle (shorter than camelina) and it can be cultivated as a winter annual crop on *unused land*. Low demand on soil and water nutrition and water. It is really frost tolerant (up to -20°C). Nowadays, it is been investigated as a promising oilseed crop in USA.	Oilseed	Oilseed for biodiesel production and aviation biofuels. Its seedcake has high protein content and can be used for bio fumigation.
Poplar	Native to most of the northern Hemisphere	South (S), Central (C), North (N)	In multibiopro project (www.multibiopro.eu) poplar had been selected as non-food crop that can be grown on marginal lands. Currently, poplar has been selected by Dedromas4Europe project (BBI, Demo).	Lignocellulosic (short rotation forestry)	Solid biofuels, advanced biofuels, biobased products (construction materials, packaging materials, etc.) paper & pulp.
Reed canary grass	North of Europe (perennial crop with lifespan 10-15 years)	Central (C), North (N)	It is reported as appropriate to be cultivated on *marginal lands* of the north (where it can grow well on both dry and wet areas), pH 4.9 to 8.2.	Lignocellulosic; 20000 ha in North of Europe.	Solid biofuels, advanced biofuels, other industrial applications.

Name (common & Latin) and family	Origin	Where can be grown in Europe	References about its suitability to be grown on marginal lands	Category	Products and markets
Safflower	It can be found in Asia, Africa and Europe.	South (S), Central (C)	It has a *strong taproot and thus thrives in dry climates*. It can be cultivated as both winter and spring crop.	Oilseed	Seeds (birdfeed), Oil (edible), dyes, medicines, etc.
Siberian elm	Native to central Asia	South (S), Central (C), North (N)	Ulmus pumila is often found in *abundance along railroads* and in abandoned lots and on disturbed ground.	Lignocellulosic (perennial crop)	Solid biofuels, advanced biofuels, biobased products paper & pulp.
Switchgrass	Native of USA	South (S), Central (C), North (N)	It has been selected by OPTIMA project (www.optimafp7.eu) as a promising crop to be grown on marginal lands. Large variety of cultivars and thus can be successfully been cultivated in all Europe.	Lignocellulosic (perennial with lifespan 10-20 years).	Solid biofuels, advanced biofuels, other industrial applications.
Tall wheatgrass	Native of Eurasia	South (S)	A very tolerant plant, able to grow in a wide range of conditions. It succeeds in soils with a pH of 5.3 - 9.0, and thrives in areas subject to *inundation by saline water*, such as seashores and saline meadows as well as on alkaline soils.	Lignocellulosic (perennial crop)	It is used as forage and for hay in many places. Source of biomass (lignocellulose). It can be used for soil reclamation.
Wild sugarcane	Native to Indian Subcontinent	South (S), Central (C)	It had been tested in OPTIMA project (www.optimafp7.eu) as a native perennial grass that can be grown on marginal lands in the Mediterranean region.	Lignocellulosic	Solid biofuels, advanced biofuels, other industrial applications
Willow	Native of North Europe	Central (C), North (N)	Grows in a variety of soils with pH 5-7.5. Its roots stand highly anoxic conditions and thus can be planted in waterlogged conditions. Due to its high tolerance to soils with heavy metals it can be used for phytoremediation.	Lignocellulosic (short rotation forestry)	Solid biofuels, advanced biofuels, biobased products (construction materials, packaging materials, etc.) paper & pulp.

Table A 2: Overview of the 44 identified constraints (adapted from the results of WP2).

Constraint / constraint combination (not MAEZ)			
Name	Abbreviation	Area (AEZ 1-3) (km²)	Share of total marginal land (AEZ 1-3) of constraint (%)
Rooting	RT	155,519	24
Climate	CL	112,096	17
Wetness	WT	108,081	17
Terrain	TR	48,404	7
Rooting - Terrain	RT - TR	32,449	5
Climate -Rooting	CL -RT	32,332	5
Climate - Wetness	CL - WT	30,105	5
Fertility	FE	23,538	4
Chemical	CH	22,512	3
Climate -Fertility	CL -FE	18,342	3
Wetness -Rooting	WT -RT	12,634	2
Climate -Terrain	CL -TR	8,686	1
Climate -Rooting - Terrain	CL -RT - TR	6,462	1
Climate - Wetness -Rooting	CL - WT -RT	5,098	1
Climate - Wetness -Terrain	CL - WT -TR	4,736	1
Climate -Fertility -Rooting	CL -FE -RT	4,416	1
Climate -Fertility -Rooting - Terrain	CL -FE -RT - TR	4,416	1
Climate - Wetness -Rooting - Terrain	CL - WT -RT - TR	4,385	1
Climate -Fertility -Terrain	CL -FE -TR	3,933	1
Wetness -Terrain	WT -TR	2,962	1
Fertility -Rooting	FE -RT	2,160	< 0.5
Climate - Wetness - Fertility	CL - WT - FE	1,938	< 0.5
Wetness -Rooting - Terrain	WT -RT - TR	1,220	< 0.5
Wetness - Fertility	WT - FE	1,195	< 0.5
Climate -Chemical	CL -CH	1,173	< 0.5
Fertility - Chemical	FE - CH	1,151	< 0.5
Chemical -Terrain	CH -TR	973	< 0.5
Climate - Wetness - Fertility -Rooting	CL - WT - FE -RT	882	< 0.5
Chemical - Rooting	CH - RT	582	< 0.5
Wetness -Chemical	WT -CH	430	< 0.5
Climate - Wetness - Fertility -Terrain	CL - WT - FE -TR	418	< 0.5
Climate - Wetness - Fertility -Rooting - Terrain	CL - WT - FE -RT - TR	250	< 0.5
Climate -Fertility - Chemical	CL -FE - CH	244	< 0.5
Fertility -Terrain	FE -TR	217	< 0.5
Wetness - Fertility -Rooting	WT - FE -RT	97	< 0.5
Wetness - Fertility -Terrain	WT - FE -TR	78	< 0.5
Climate -Chemical - Rooting	CL -CH - RT	54	< 0.5
Fertility -Rooting - Terrain	FE -RT - TR	45	< 0.5
Chemical - Rooting - Terrain	CH - RT - TR	44	< 0.5
Climate -Chemical -Terrain	CL -CH -TR	18	< 0.5
Fertility - Chemical -Terrain	FE - CH -TR	18	< 0.5
Fertility - Chemical - Rooting	FE - CH - RT	11	< 0.5
Climate - Wetness -Chemical	CL - WT -CH	5	< 0.5
Wetness - Fertility - Chemical	WT - FE - CH	1	< 0.5
Total marginal (EU-28)		646,833	
Total not marginal (EU-28)		1,666,238	

Table A 3: Suggested key factors of MALLIS to be covered within new field trials of MAGIC partners (adapted from MAGIC Grant Agreement).

Partner	AEZ	Constraints	Conversion routes	Key management issues
CIEMAT	1	Unfavorable texture &stoniness	Lignocellulosic	Minimum/no tillage
			Woody	Rainfed
	1	Dryness	Lignocellulosic	Reduced irrigation vs no irrigation
CRES	1	Unfavorable texture & stoniness	Oil	Minimum/no tillage
			Carbohydrate	Reduced fertilization
				Reduced irrigation
	1	Acidity	Lignocellulosic	Minimum/no tillage
				Reduced fertilization
				Reduced irrigation
UNICT	1	Steep slope	Oil	Minimum/no tillage
			Lignocellulosic	Reduced fertilization (incl. compost)
				Rainfed
	1	Dryness	Oil	Minimum/no tillage
			Lignocellulosic	Reduced fertilization (incl. compost)
				Reduced irrigation/rainfed
	1	Poor chemical properties (soil salinity)	Oil	Optimal fertilization /reduced fertilization (incl. compost),
				Reduced irrigation/rainfed
INRA	2	Contaminated by wastewater	Lignocellulosic	Minimum/no tillage
				Bio-fertilisation
IBC	3	Poor chemical properties (sodicity) + limited soil drainage	Carbohydrate	Minimum/no tillage
			Lignocellulosic	Reduced fertilization
				Rainfed
	3	Poor chemical properties (acidity)	Carbohydrate	Minimum/no tillage
			Lignocellulosic	Reduced fertilization
				Rainfed
	3	Contaminated by mineral fertilizers, pesticides, herbicides	Carbohydrate	Minimum/no tillage
			Lignocellulosic	Reduced fertilization
				Rainfed
SILAVA	3	Unfavourable texture & stoniness combined with low temperature	Woody	Minimum/no tillage
				Reduced fertilization
UHOH	3	Unfavorable texture & stoniness combined with low temperature	Lignocellulosic	Minimum/no tillage
			Oil	Reduced fertilization
				Weed control/reduced weed control

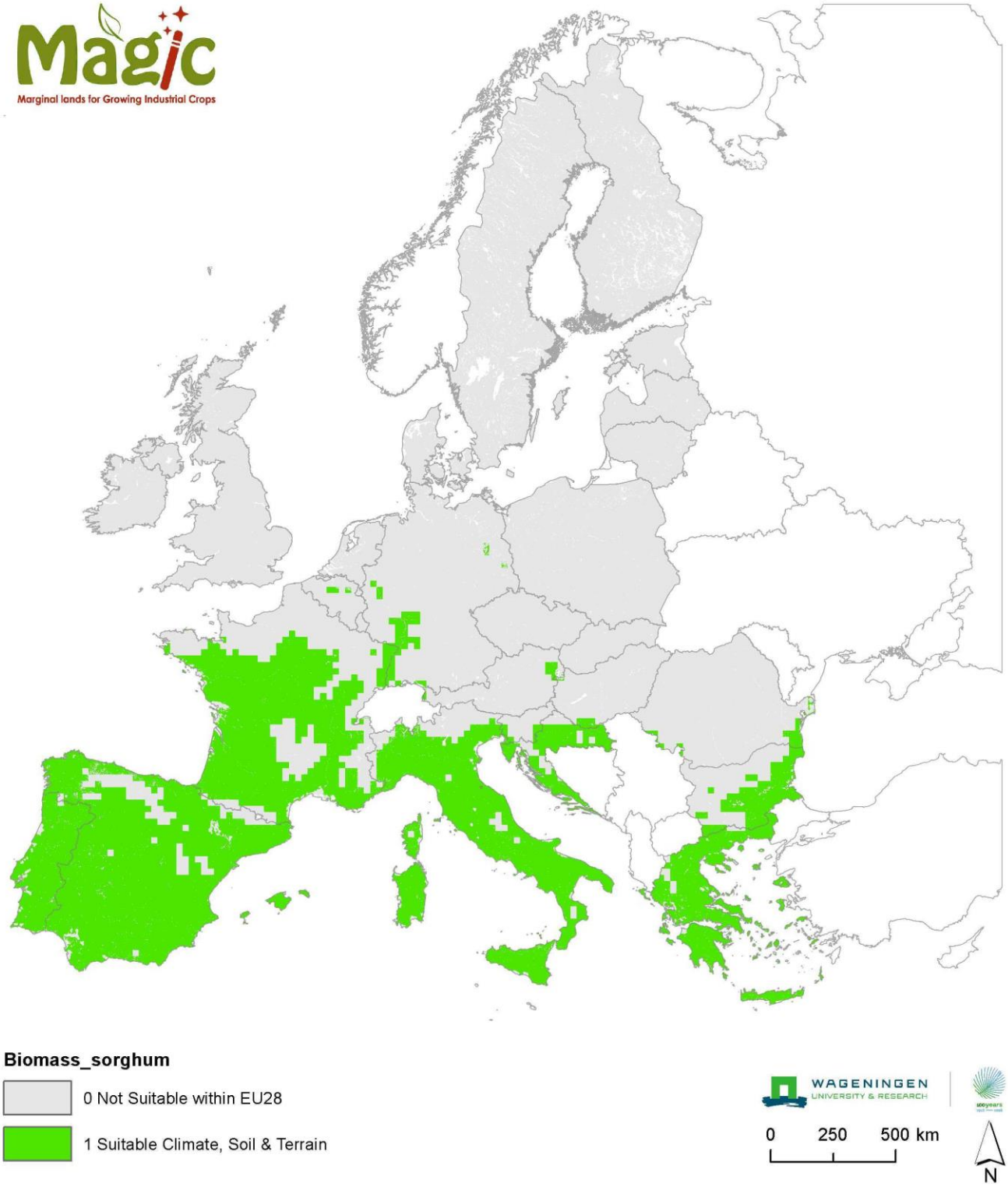

Figure A 1: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for biomass sorghum based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

Figure A 2: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for camelina based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

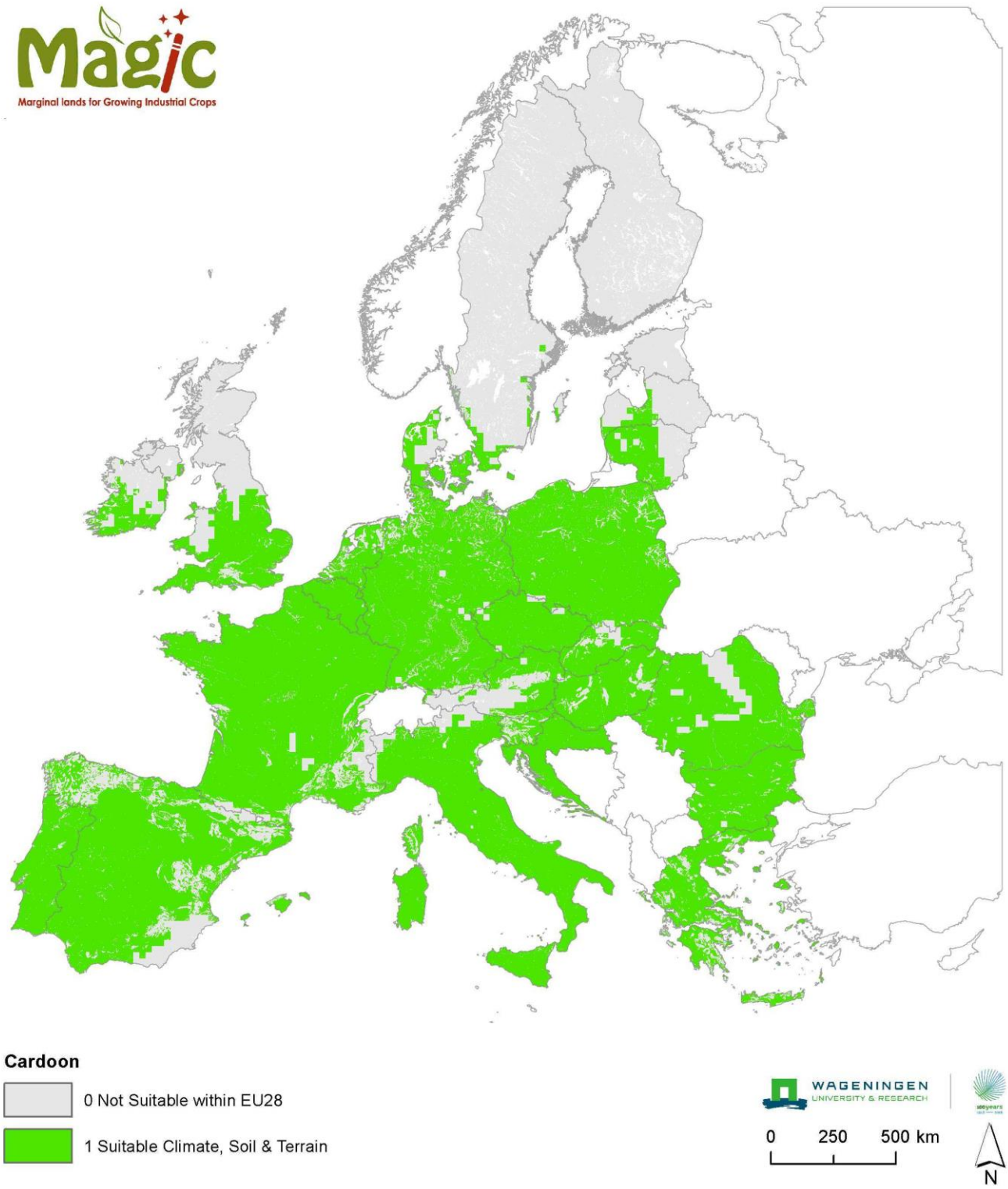

Figure A 3: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for cardoon based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

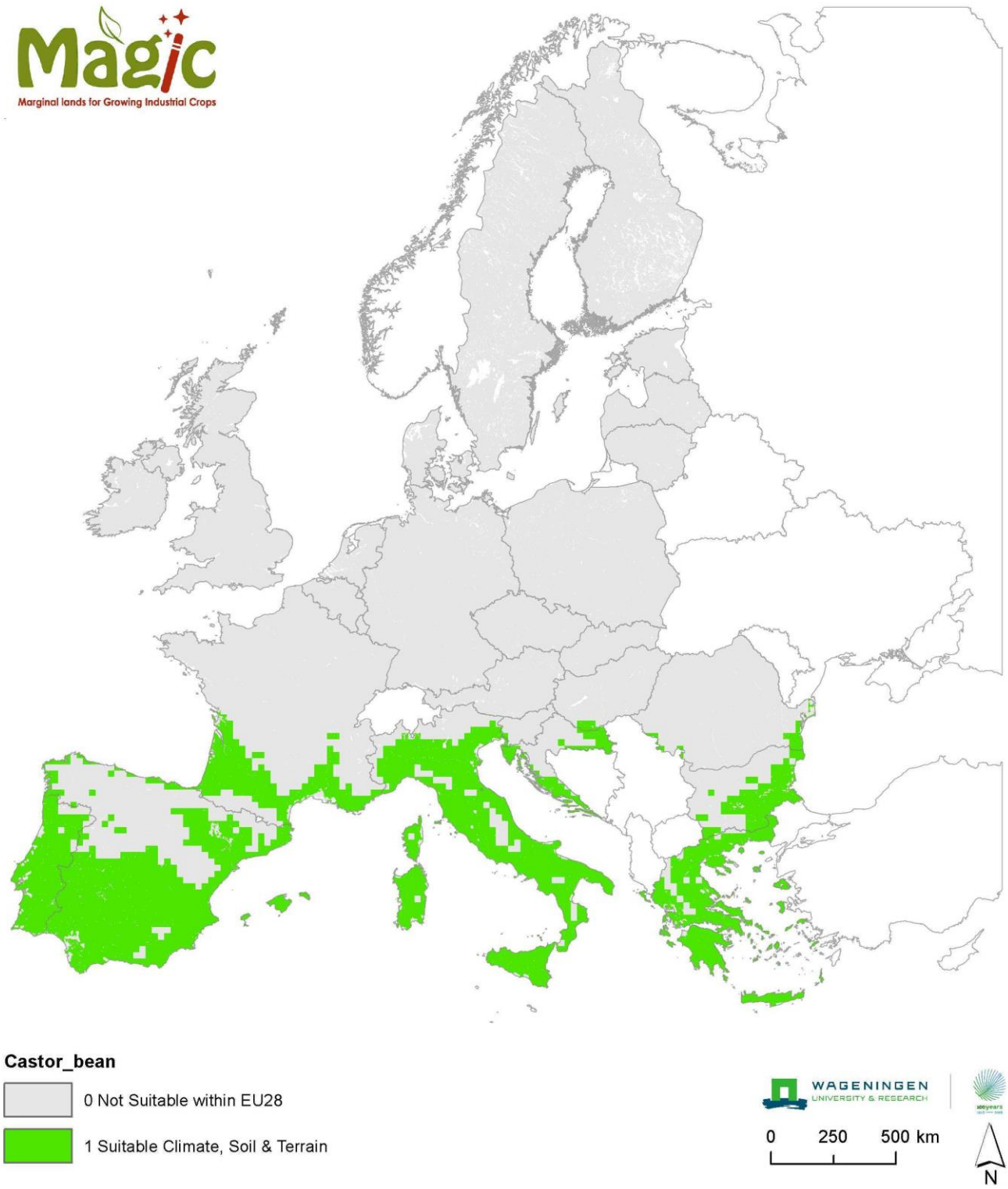

Figure A 4: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for castor bean based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

Figure A 5: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for Crambe based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

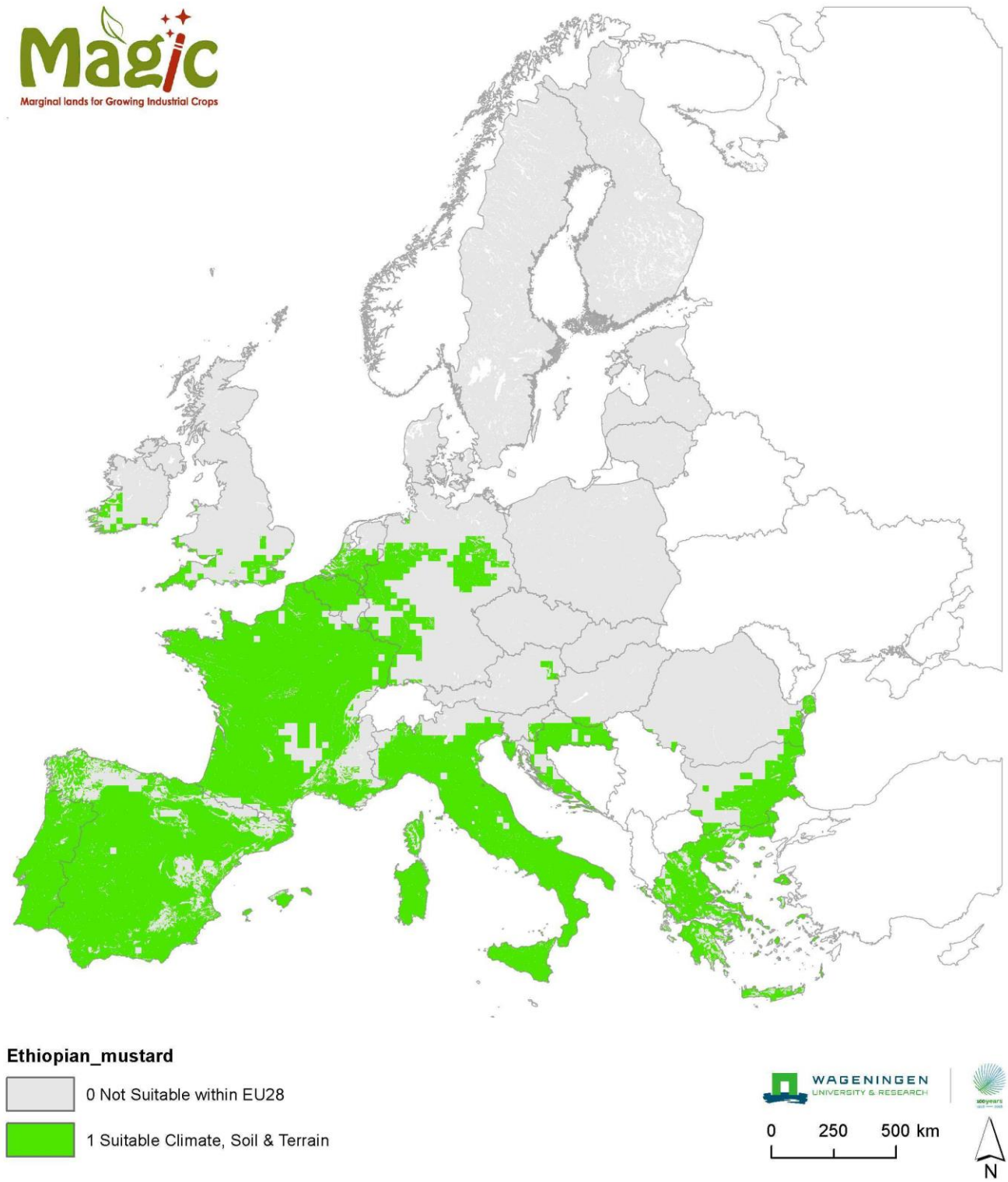

Figure A 6: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for Ethiopian mustard based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

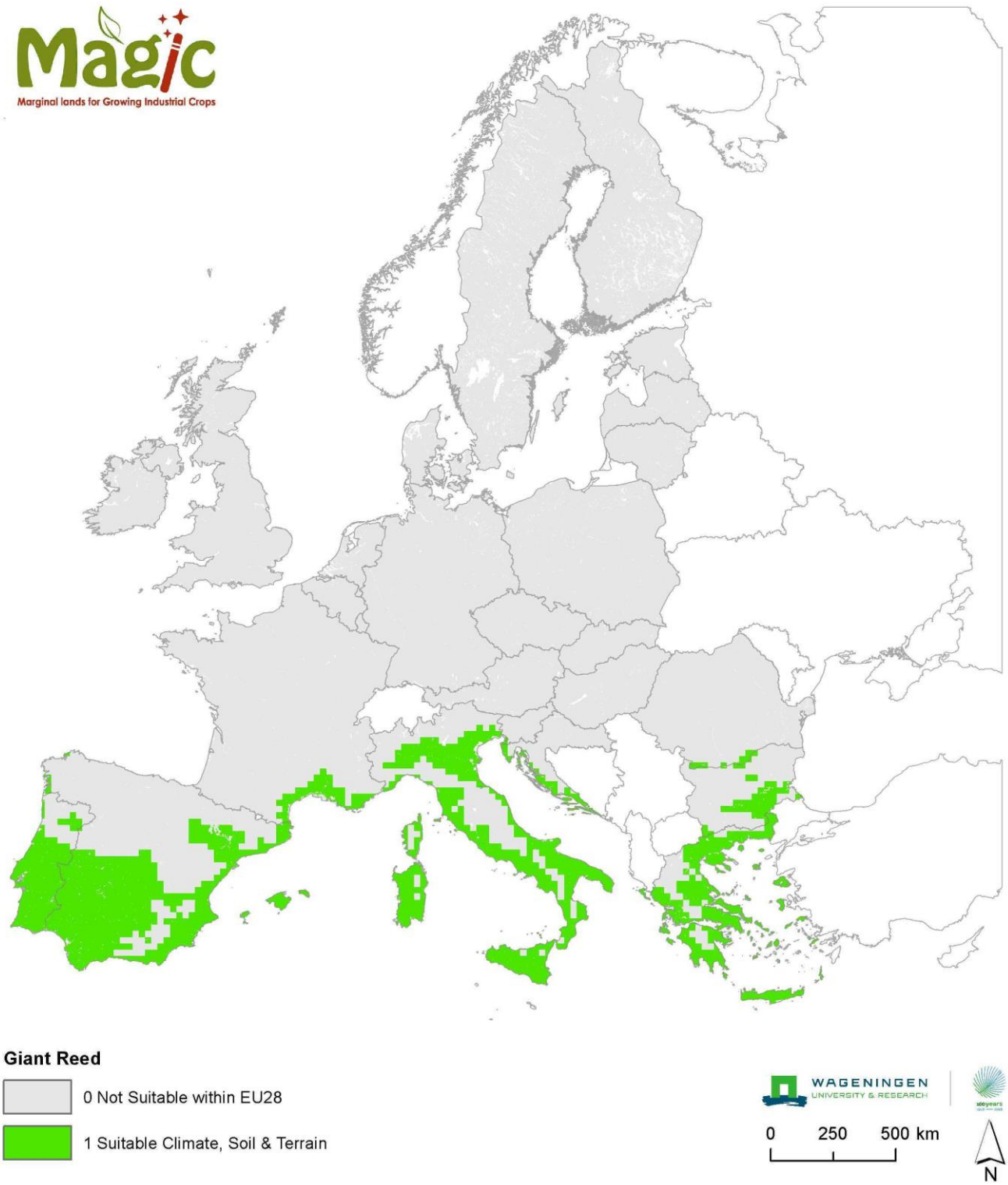

Figure A 7: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for giant reed based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

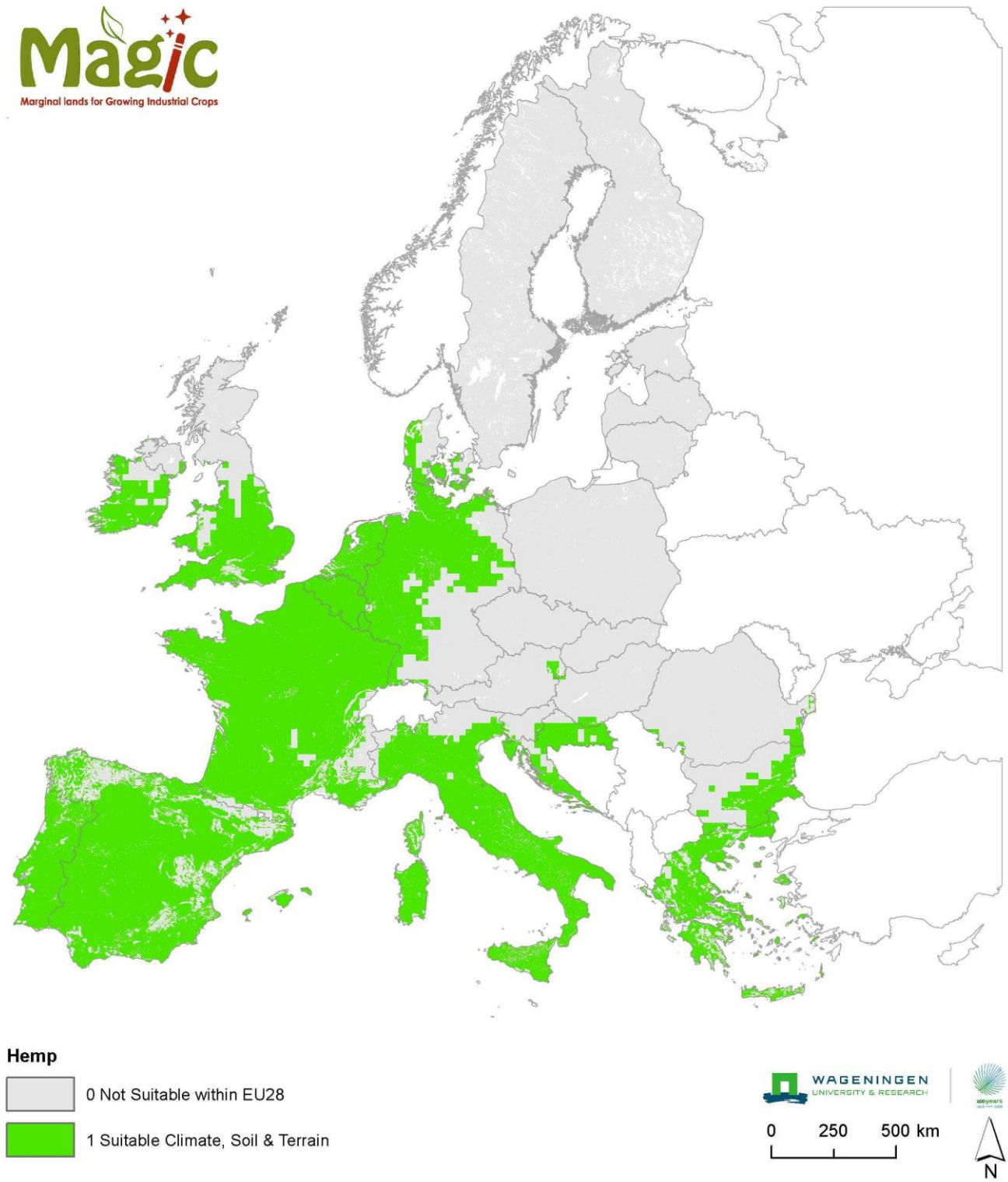

Figure A 8: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for hemp based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

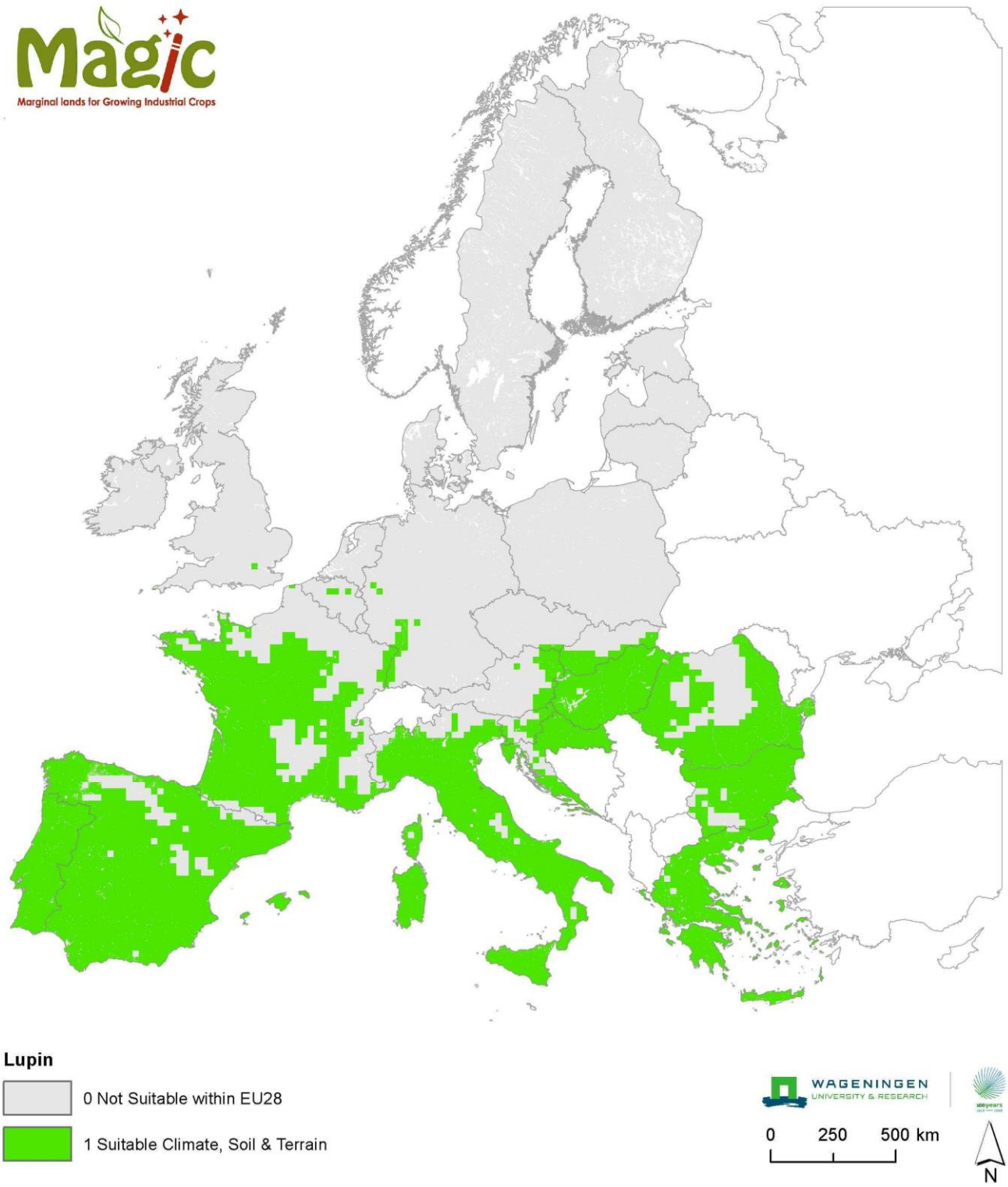

Figure A 9: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for lupin based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

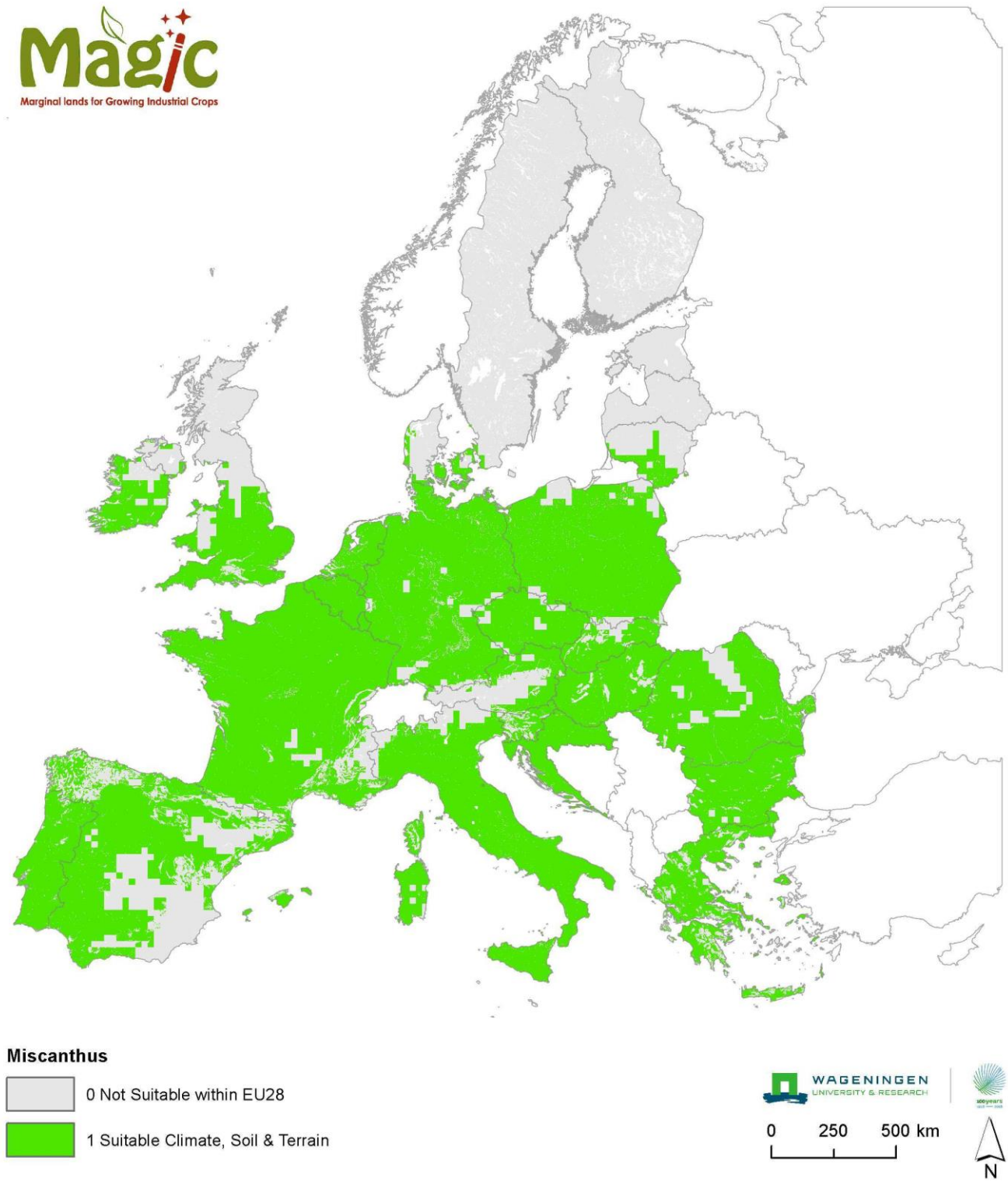

Figure A 10: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for miscanthus based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

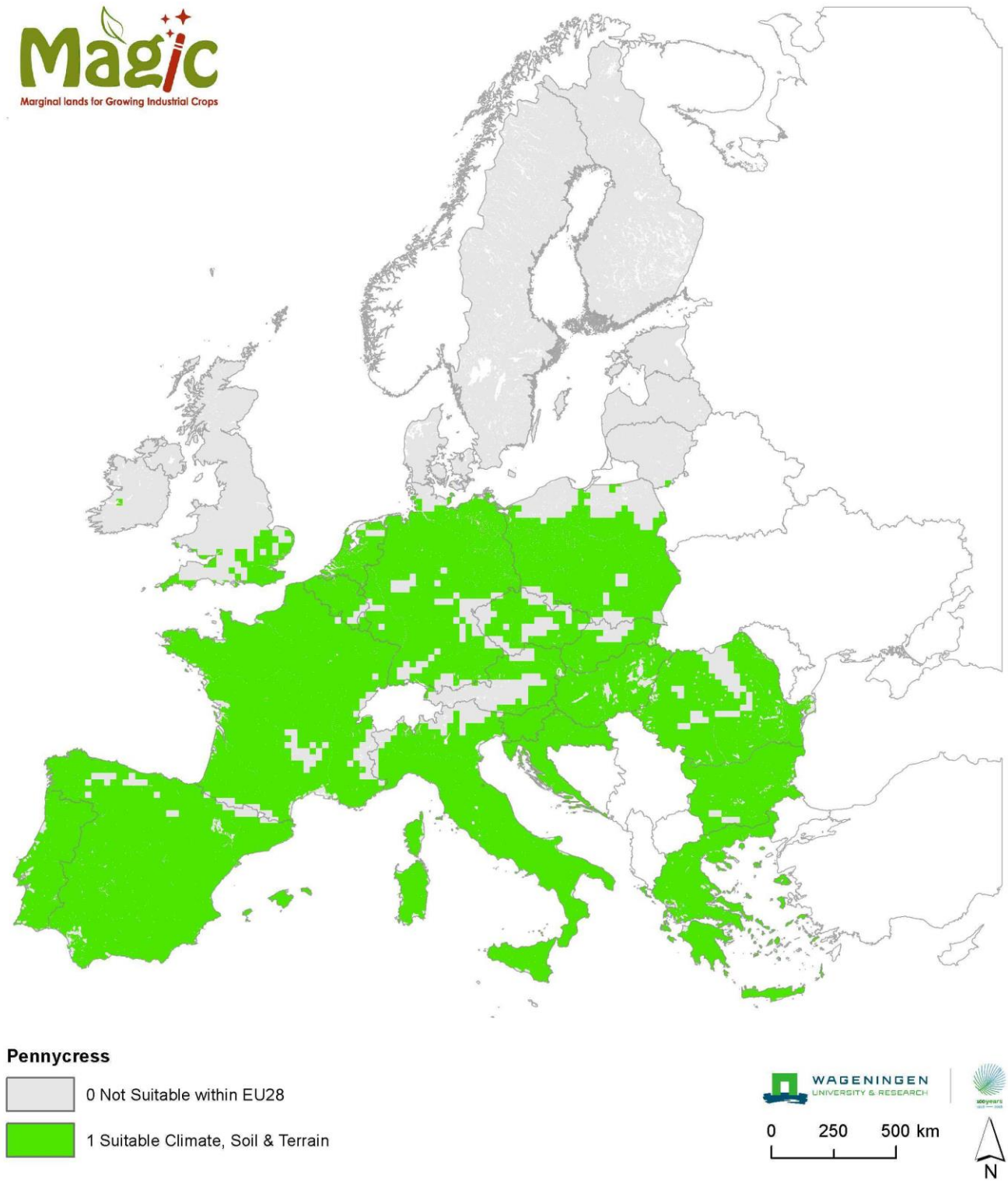

Figure A 11: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for pennycress based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

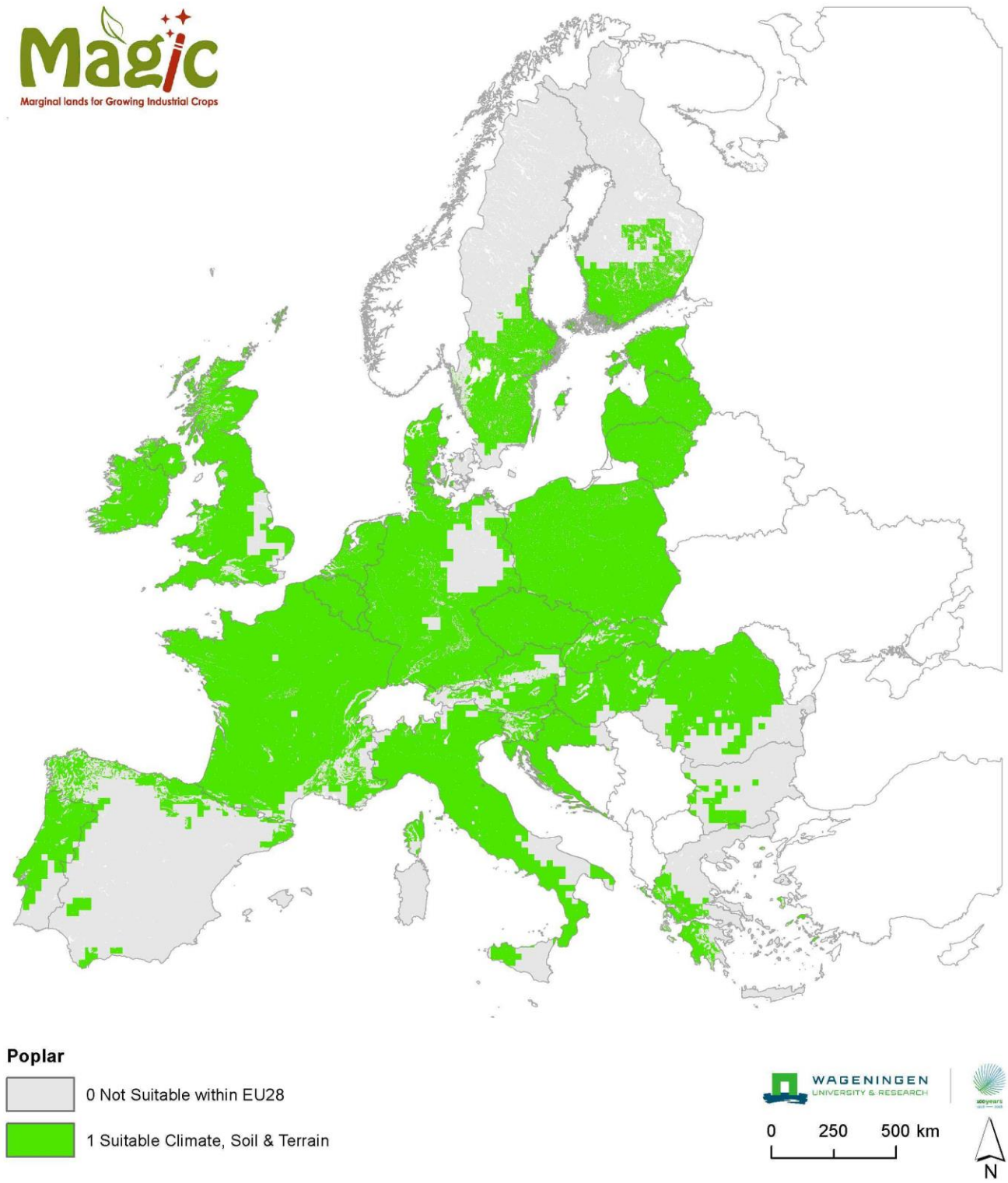

Figure A 12: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for poplar based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

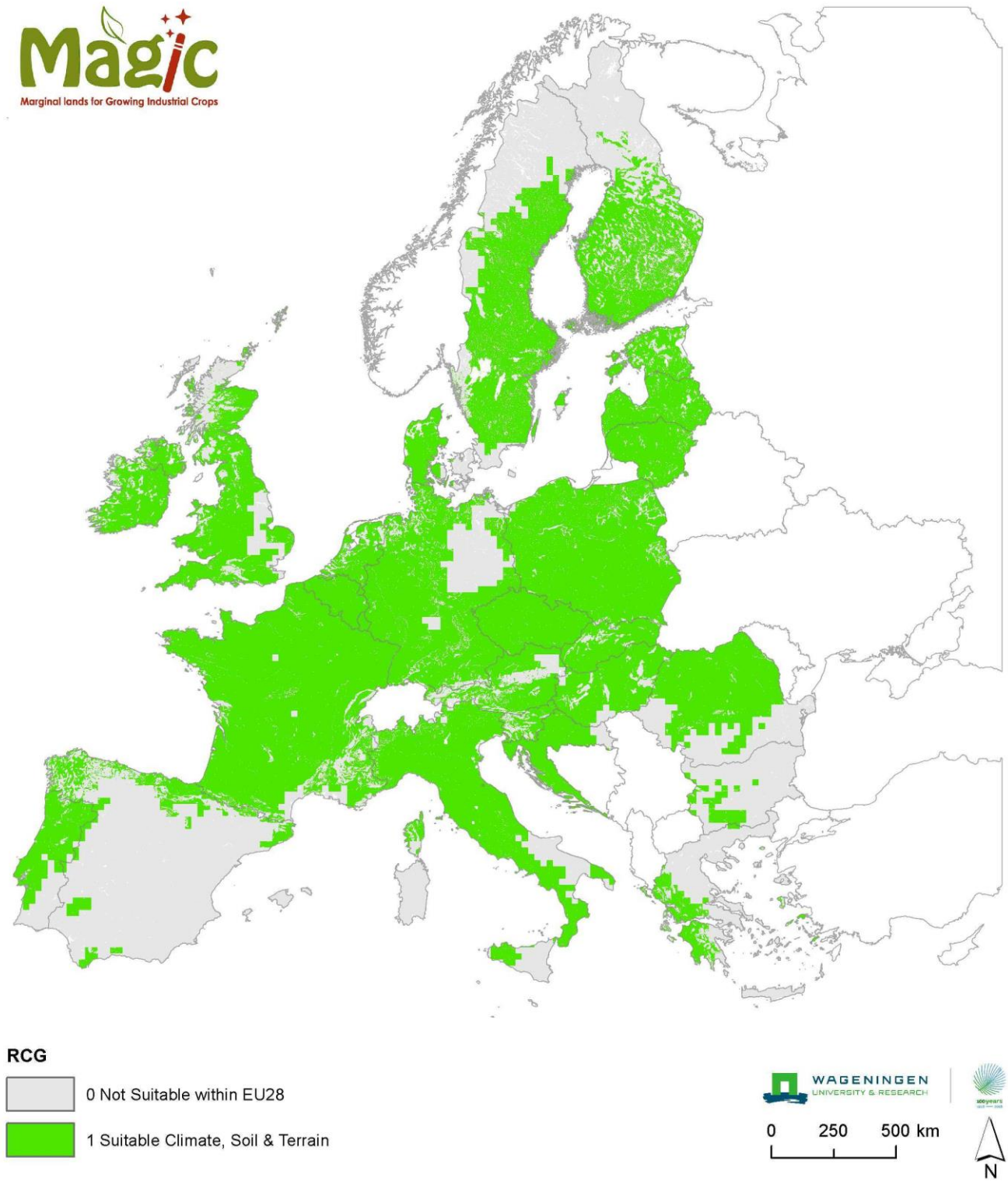

Figure A 13: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for reed canary grass based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

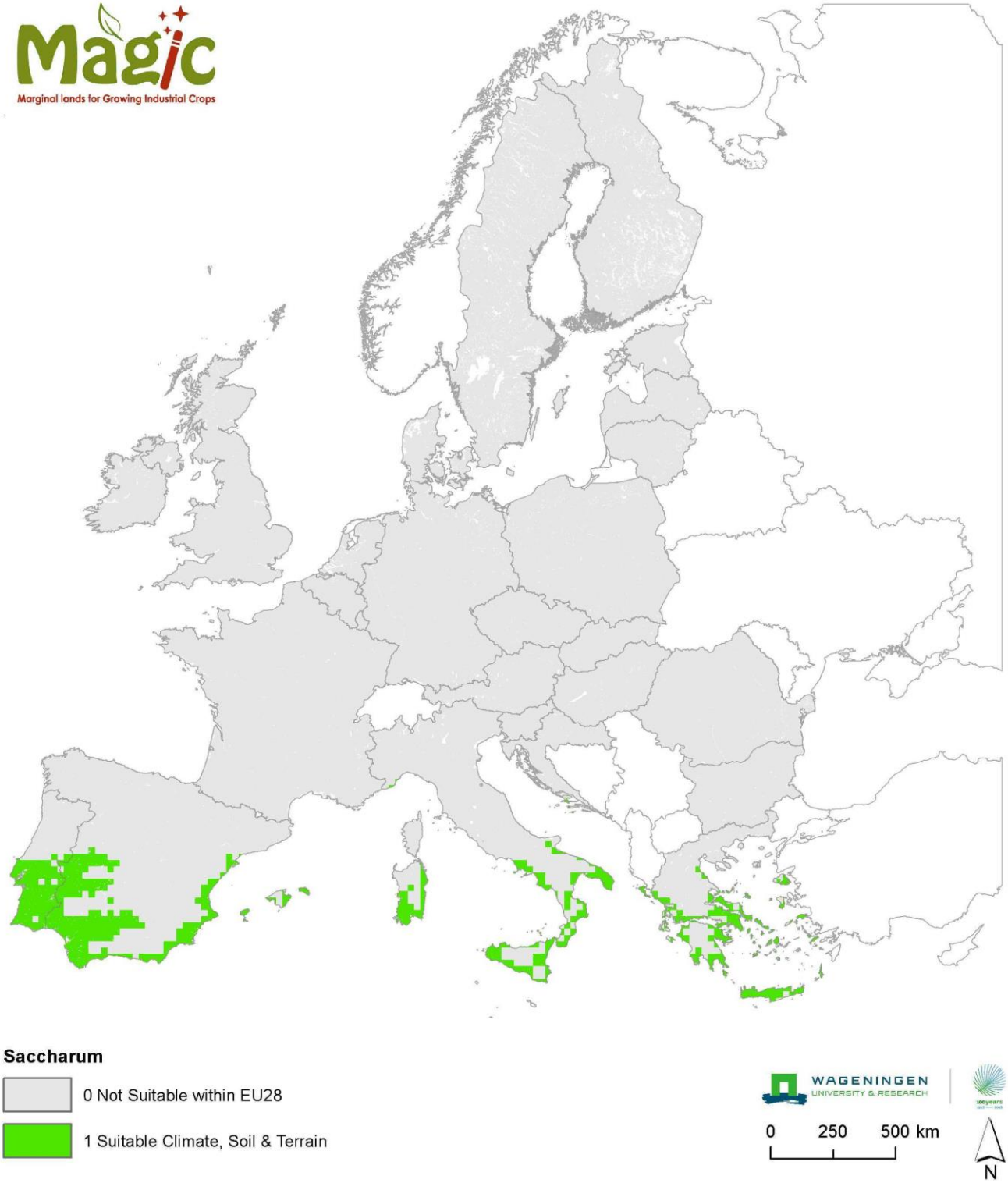

Figure A 14: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for wild sugarcane (*Saccharum spontaneum* L.) based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

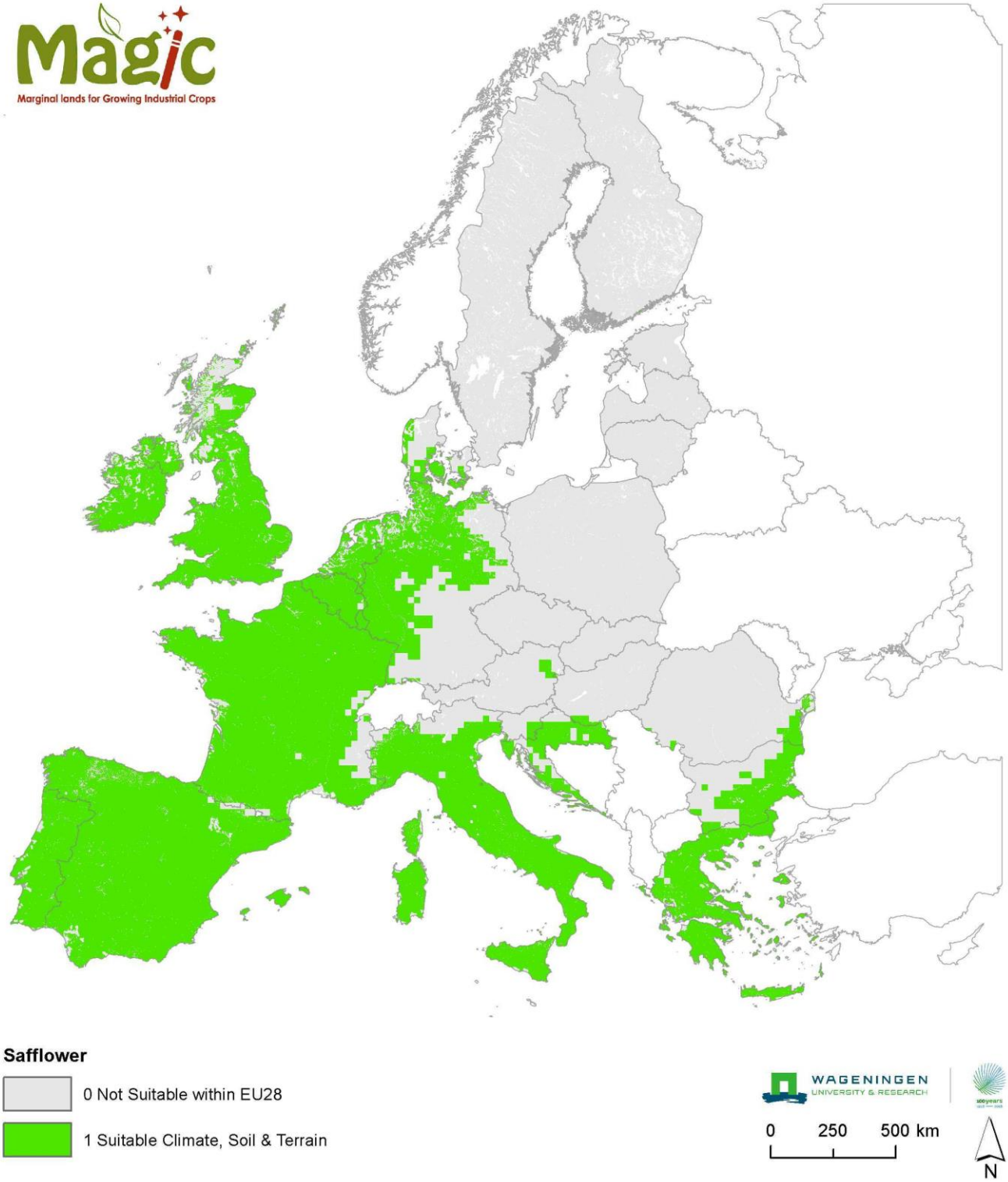

Figure A 15: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for Safflower based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

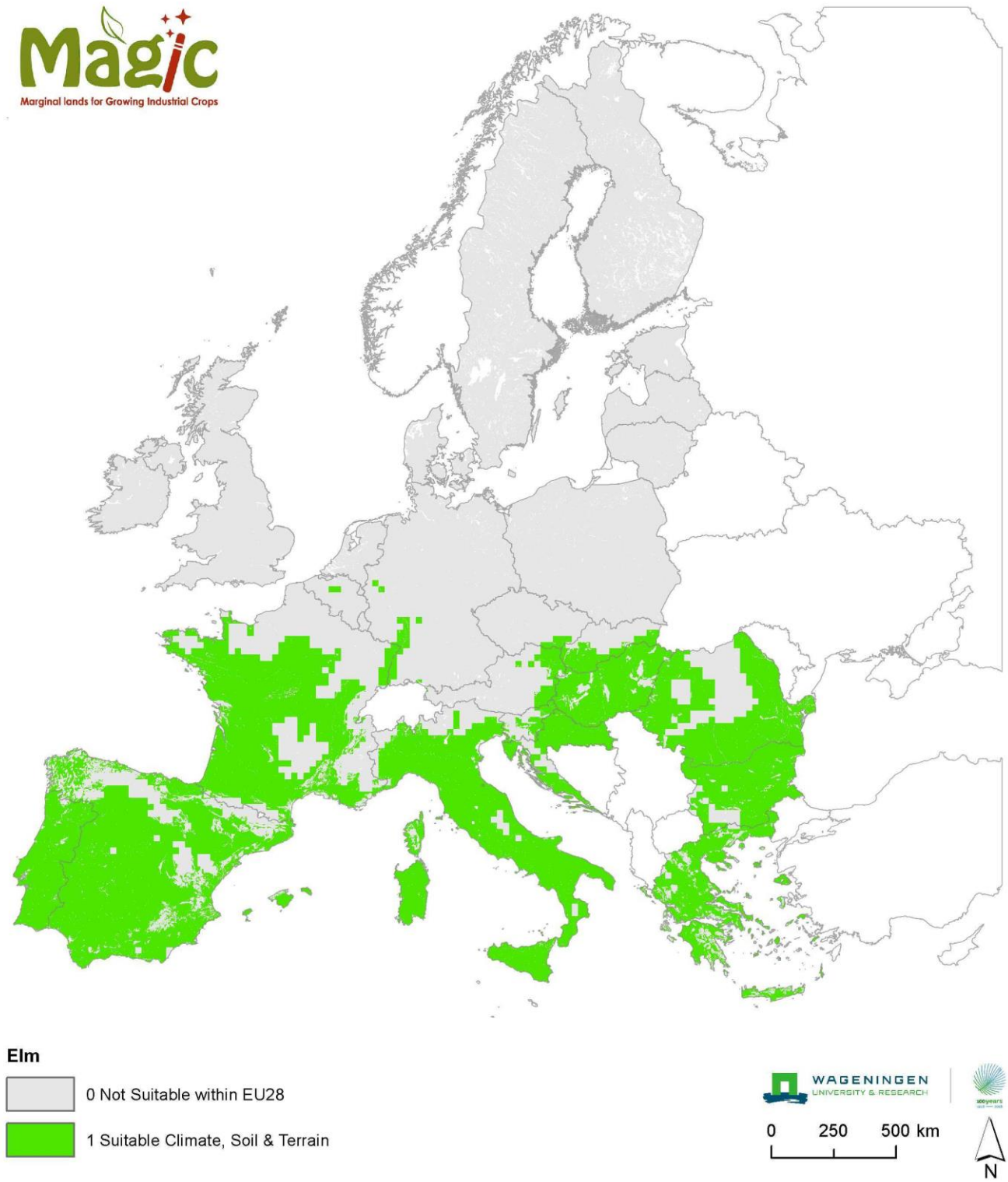

Figure A 16: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for Siberian elm based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

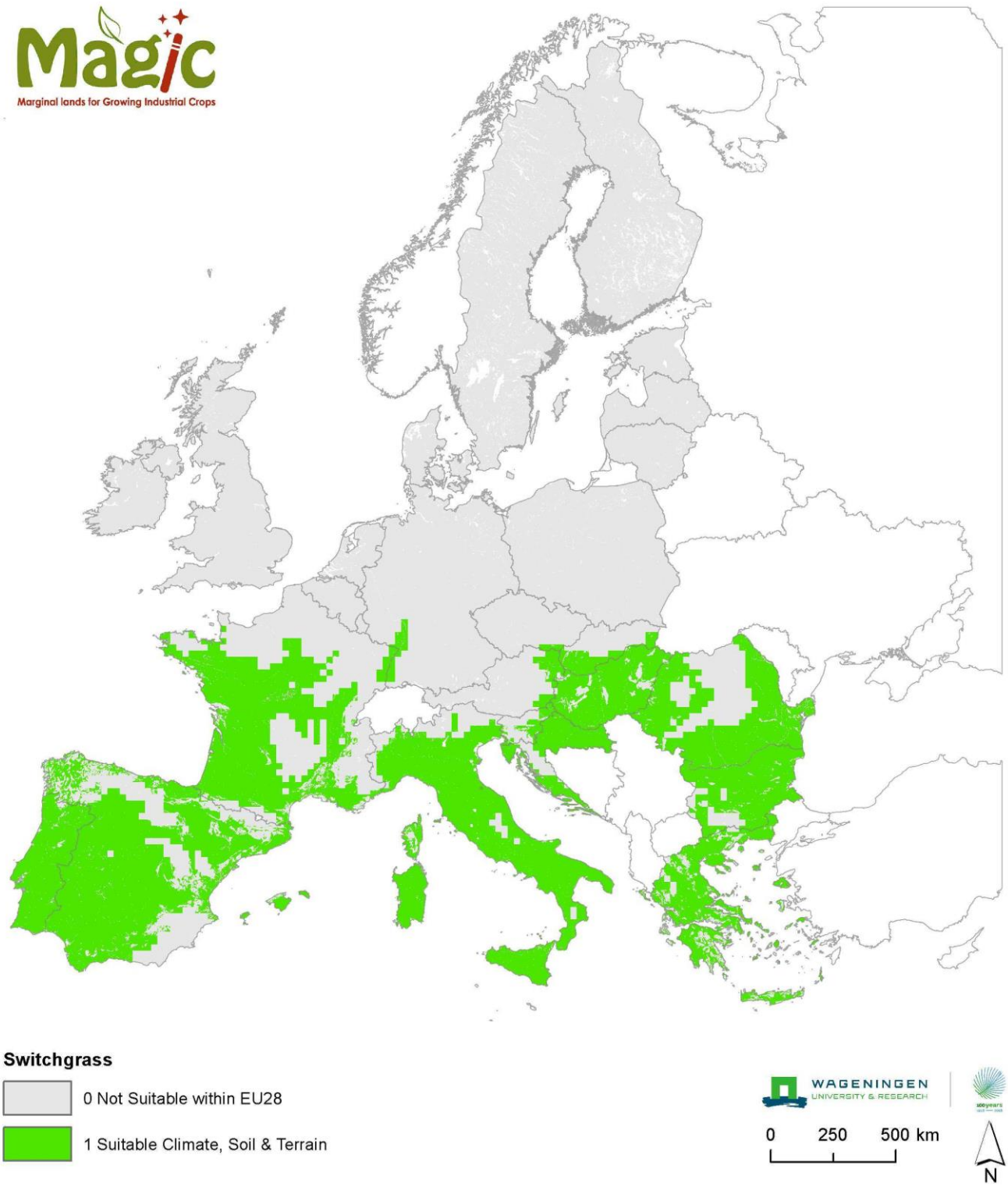

Figure A 17: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for switchgrass based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

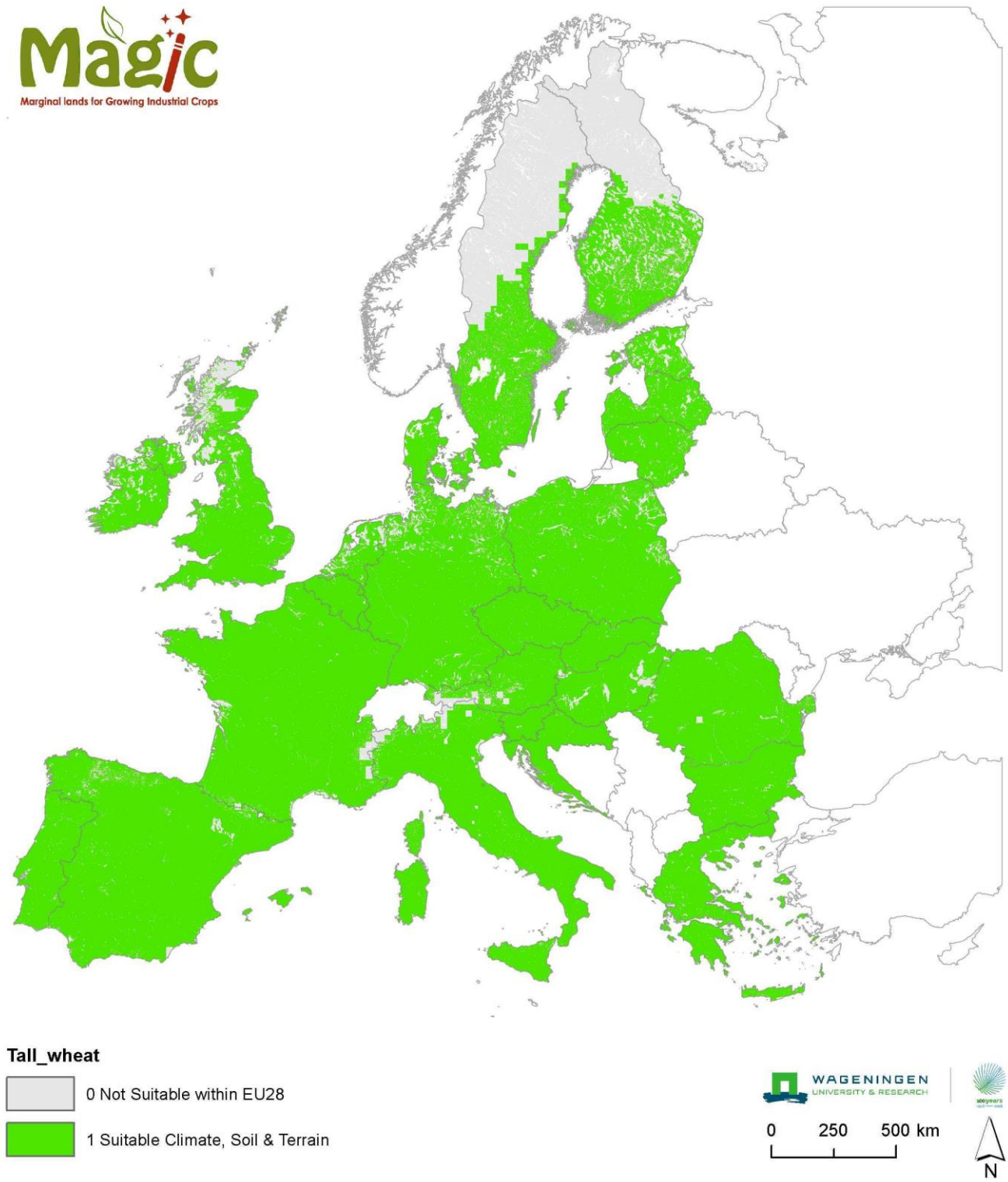

Figure A 18: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for tall wheatgrass based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.

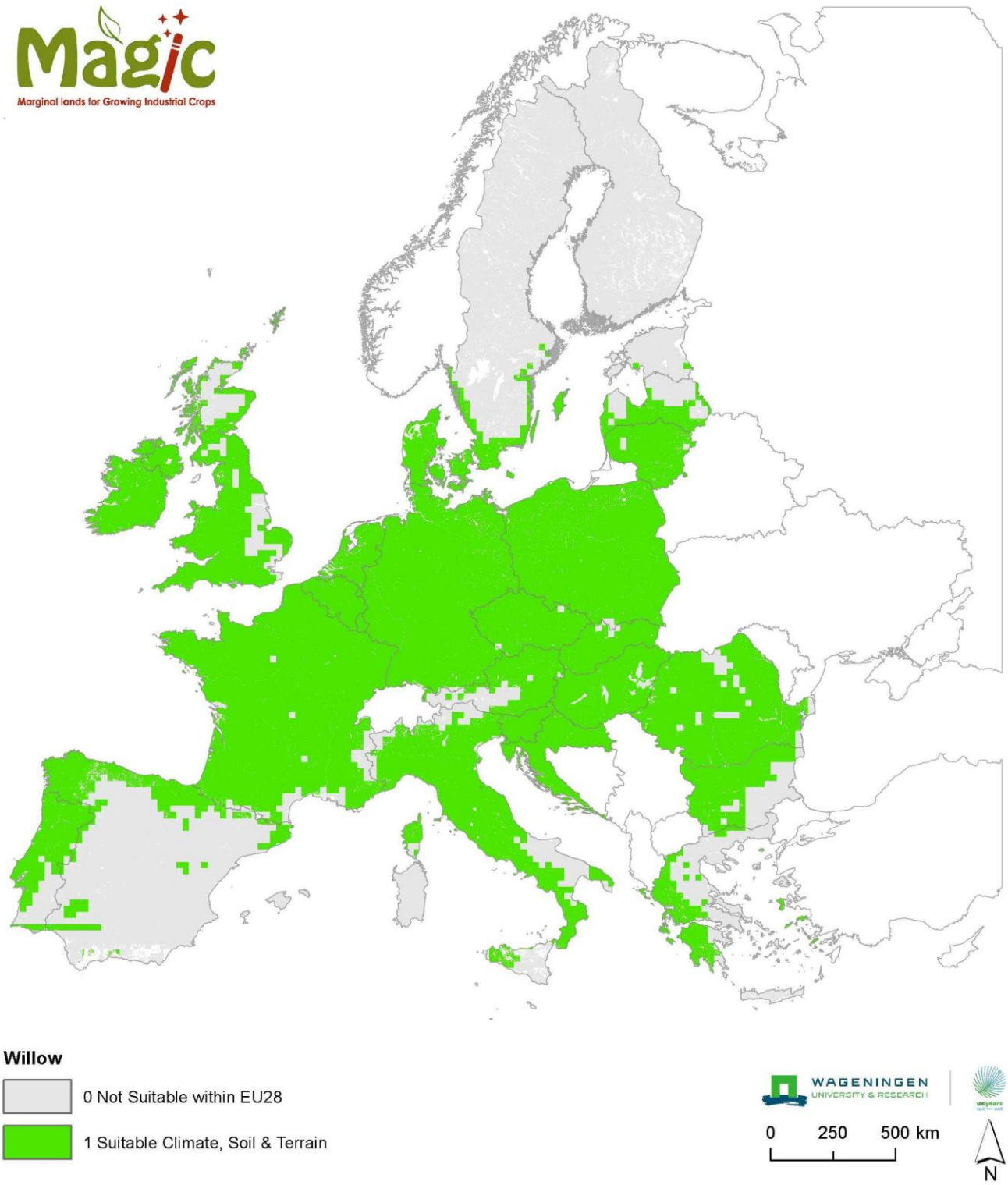

Figure A 19: Spatial distribution of suitable climate and soil/terrain conditions on both marginal and non-marginal land across Europe (EU-28) for willow based on climate and soil/terrain growth-suitability rankings presented in Chapter 2.