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Methodology and factsheets for plausible criteria combinations

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Methodology, Factsheets for plausible criteria combinations

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List of Abbreviations

ANC	Area with Natural Constraints
CAP	Common Agricultural Policy
DG AGRI	Directorate General for Agriculture and Rural Development
EC	European Commission
esd	equivalent spherical diameter
EU	European Union
FAO	Food and Agriculture Organization (United Nations)
GIS	Geographic Information System
JRC	Joint Research Centre
LFA	Less Favoured Area
MS	Member State
NUTS	Nomenclature des Unités Territoriales Statistiques
RD	Rural Development
RDP / RDM	Rural Development Programme / Rural Development Measure
UAA	Utilised Agricultural Area
WRB	World Reference Base for Soil Resources

Summary

Support for farming in areas facing natural constraints aims at compensating farmers for disadvantages due to adverse conditions. EU regulation No 1305/2013 provides grounds to delineate, amongst others, ‘areas with specific constraints’ through the combination of biophysical criteria of Annex III when at least two of the biophysical criteria are present within a margin of not more than 20% of the threshold value initially defined.

An ad-hoc panel of experts, under JRC steering, has prepared guidance and recommendations on the plausible combination of criteria and relevant sub-severe thresholds. However, the experts have also underlined the uncertainties of this exercise due to data availability and the complexity of soil-climate-plant interactions.

The eight biophysical criteria (indeed 14 sub-criteria) were cross-tabulated to examine the resulting 91 pairwise combinations. These can result in negative or positive synergies, no interaction, unclear synergy; plus some combinations which are unlikely to occur or are not possible. Moreover, specific cases were also identified where criteria combinations are not appropriate (e.g. when criteria are conceptually linked).

An assessment of the threshold values towards the 20% margin was carried-out and revealed that the application of the exact threshold value is not always possible or reasonable. As a consequence, five approaches to this situation were defined and accordingly recommended to the concerned criteria. For each criterion, the rationale and justification for the sub-severe threshold application are provided in the document. For the combination of criteria, factsheets were prepared for all negative (25 cases), positive (3 cases) and unclear synergies (5 cases).

The scientific recommendations in the report are without prejudice to the legal framework of Regulation 1305/2013.

1 Introduction

The present report aims at providing guidance and recommendations on how to possibly delineate 'Areas with Specific Constraints' based on provisions laid-down in Article 32.4 of EU regulation 1305/2013. More specifically, it addresses the possibility of combining two criteria listed in Annex III of the above cited regulation, both within a margin of 20% of the indicated threshold value.

The report has three main sections, starting with a brief description of the policy context underpinning the revision of the Areas with Natural Constraints in Europe, focussing on the Areas with Specific constraints.

Follows a description of the methodological framework to come in a description of possible interactions and synergies, and in spelling-out five cases proposed to apply the 20% margin sub-severe threshold where scientific rationale and justification are given for each biophysical criterion. The assessment of the criteria pair-wise combinations are made through cross-tabulation, leading to the identification of six different situations, from which three are proposed to be relevant for the delineation exercise.

These are described in the third section dedicated to factsheets for negative, positive or unclear synergies.

The scientific recommendations in the report are without prejudice to the legal framework of Regulation 1305/2013.

1.1 Policy context and background information

1.1.1 Revision of the ANC delineation

Support for farming in mountain areas or in other areas facing natural constraints aims at compensating farmers for disadvantages to which the agricultural production is exposed due to adverse biophysical conditions related to soil, climate, and slope. Support is also possible for other specific constraints where continued management of the land is necessary to conserve or improve the environment, to maintain the countryside, to preserve the tourist potential or to protect the coastline. Such areas were referred to 'Less Favoured Areas' (LFA) in the past. This compensation shall allow farmers to continue using agricultural land, maintain the countryside as well as maintain and promote sustainable farming systems in the areas concerned in order to prevent land abandonment and loss of biodiversity.

The areas, other than mountains, facing such natural or other specific constraints, are subject to changes in delimitation and other requirements compared to the programming period 2007-2013. The three categories of these payments 'mountain areas', 'areas facing natural constraints' and 'areas with specific constraints' (ANC) will remain during the period 2014-2020, but the novelties introduced in the Rural Development Regulation for the period 2014-2020 result in the delineation obligation for EU Member States (MS) for 'areas facing natural constraints' and an optional new possibility for delineating 'areas with specific constraints'.

Consequently, EU Member States are engaged in an exercise to revise the designation of areas facing natural constraints (other than mountain) and (if relevant) areas with specific constraints. While the designation of mountain areas has not changed, new criteria have been adopted by the regulation (EU) No 1305/2013 of the European Parliament and of the Council of 17 Dec. 2013 on support for rural development by the European Agricultural Fund for Rural

Development (EAFRD). The methodology for the designation is defined in Article 32, while the criteria are listed in Annex III of the same regulation.

A set of eight biophysical criteria (and associated critical thresholds) to be used for the designation of areas (other than mountain) facing significant natural constraints has been defined by experts in land evaluation. The application of the methodology relies on the agronomic Liebig's law of the minimum, such that indicators can be used as criteria to classify land in EU-28 in two broad classes: (i) land without significant soil and/or climate and/or slope constraints to agriculture, and (ii) land with severe soil and/or climate and/or slope constraints, restricting agricultural activity. Constraints were considered for a typical mechanized conventional European farm unit producing grain crops or grass to support stock rearing. The set of indicators are in-line with an extension of FAO's 'problem land' (for agriculture) approach, while the threshold values were derived from state-of-the-art scientific knowledge and expert consultation. The factsheets of the common biophysical criteria are described in Van Orshoven et al. (2014).

1.1.2 Delineation of areas with specific constraints

While areas facing natural constraints (other than mountain) are defined with the eight biophysical criteria (regulation EC (EU) 1305/2013, Art. 32.3), other areas are also eligible for payments if they are affected by specific constraints and if land management should be continued in order to conserve or improve the environment, to maintain the countryside, to preserve the tourist potential of the area or to protect the coastline (regulation EC (EU) 1305/2013, Art. 32.4).

Member States have considerable flexibility to designate areas with specific constraints (due to their inherent specific nature). In addition, the newly adopted regulation provides the MS with an extra possibility to combine biophysical criteria of Annex III to designate ANC 'specific' when at least two of the biophysical criteria are present within a margin of 20% of the threshold value defined.

2 Methodological framework

Since the negotiations between the Council, the European Parliament and the European Commission have foreseen the possibility for applying 'combined' criteria in defining areas facing specific constraints, DG AGRI commissioned the Joint Research Centre (JRC) to provide more detailed guidance on this matter. In response, the JRC formed a new panel comprising four external experts coming from European research organisations, supported by three staff of the JRC.

Scientists in the expert panel have extensive experience and publications in the field of soil science, agro-meteorology, crop growth modelling, land evaluation and crop suitability, agro-ecological zoning, GIS analysis and soil mapping.

In the initial land evaluation scheme foreseen to delineate areas (ANC) with significant natural constraints to agriculture (other than mountain), individual criteria were applied according to the law of the minimum (Liebig's law). This means that as soon as one of the criteria is rated as 'severely limiting', the corresponding land is considered to have severe limitations for agricultural production. This approach assumes that, <u>at the severe threshold level</u>, each criterion has a distinct influence on the suitability of the land and the constraint for agricultural production is certain. In that configuration, criteria act independently from each other. This framework has been validated by state-of-the-art scientific knowledge and expert consultation (see Van Orshoven et al., 2014).

In addition to the relatively simple, applicable and robust framework described above, the legislator inserted the possibility to combine individual biophysical criteria within a margin of 20% of their initial threshold values to identify areas affected by specific constraints to agriculture.

While life sciences recognise the complexity of nature and agronomy (which is about interactions between soil and climate conditions and their impacts on crop production), it is acknowledged that interactions and synergies in the cropping environment cannot be fully qualified, quantified and assessed against any unique fixed value. Moreover, crop production does not respond in a linear mode to these interactions. This kind of evaluation has a greater degree of uncertainty in scientific rationale and can be estimated only with more detailed (site specific) data and often through a process-based modelling approach. Unfortunately, such data are not available semantically and geographically at the scale of Europe and often not at national or regional level either.

Indeed, the group of experts had some reserved views on this exercise and underlined the '*thin ice*' character of some of the rationale, justification and sub-severe threshold levels for some criteria combinations.

Moreover, the additional complexity of possible criteria combinations raises concerns about their applicability on the ground and their relevance for policy implementation.

Given the specialised domains (agro-meteorology, crop growth/crop physiology, soil science) and the multiplicity of possible situations (pair-wise combination with eight criteria), guidance was requested to an expert panel to support DG AGRI and the Member States on the plausible combination of criteria for the delineation of areas with specific constraints.

Without prejudice to the legal framework of Regulation 1305/2013, the present document's objectives are:

i. To explore options within the legal framework to sensibly combine biophysical criteria;
ii. to provide guidance and recommendations on the typology of interactions between criteria;
iii. to assess the adequate sub-severe thresholds (within the margin of 20% of the initial value indicated in Annex III) which could still trigger a limitation to agricultural activity;
iv. to provide factsheets for each possibly occurring (negative, positive, unclear) combination of the eight biophysical criteria; and
v. to identify unrealistic or non-interacting criteria combinations.

2.1 Combinations and types of interaction

In this document, the eight biophysical criteria (14 when counting all sub-criteria, e.g. *organic soil* is a sub-criterion within the *Unfavourable texture and stoniness* criterion) were cross-tabulated to examine the resulting pair-wise combinations and possible interactions. The aim was to propose additions to the initial evaluation scheme in case such interactions should be

considered influential. The resulting pair-wise combinations of 14 criteria yield 91[a] distinct cases that have been examined.
In principle, interactions could be studied between more than two criteria, but this was judged to be too complex and beyond the scope of this exercise. Moreover, combinations of 3 or more criteria should not be necessary as they already contain the combinations of 2 criteria described in this report.

For each pair, the following questions were addressed in order to detect possible interactions:

i. Do two sub-severe constraints (below individual thresholds for severe limitation) result in a combined 'severe' limitation (called in this document 'negative synergy')?
This is where the individual criteria are not likely to constrain agricultural activity according to the threshold indicated in Annex III of regulation (EU) No 1305/2013 but they are present at sub-severe level and when combined, their interaction could exacerbate the effect of each individual criterion, resulting in a severe constraint to agriculture. Experts were requested to provide justification through the description of the agronomic rationale, scientific background, meaningful sub-severe thresholds for the combination, and likely situations where the combination can occur, supported by literature references.
ii. Do two sub-severe constraints result in a combined rating of 'no severe limitation' (called in this report 'positive synergy')? This applies to two criteria that individually present a sub-severe limitation to agriculture, with their characteristics compensating each other and not fostering any severe constraint. Explanations for these situations are provided as it is important to have a robust basis to combine criteria to provide guidance and to ensure the credibility of the whole biophysical criteria framework for the delineation of areas with natural constraints.

Table 2 shows for each of the 91 possible pair-wise combinations the expert-assessment of positive or negative synergies. These pairs are described in more detail in the form of factsheets, presented in section 3.

In addition to those two possible assessments (positive or negative synergy), the evaluation detected supplementary possibilities:

iii. No interaction: when there is no interaction between the combined criteria, the combination does not generate a severe constraint for agricultural production. Both criteria impacts are independent (e.g. *Shallow rooting depth* and *soil acidity*), thus synergy (positive or negative) does not occur. Their combined presence, at sub-severe level, does not generate a severe limitation to farming conditions as their effects apply separately on crops' productivity. In this case, there is no reason to depart from the original framework based on the Liebig's law of the minimum. As the rationale for Article 32 presumes a constraint to agricultural production, softer thresholds of some criteria combinations do not always constitute a limitation and thus, such situations cannot be quantified and expressed in terms of income loss and additional costs. In these cases, the criteria should be applied individually at the threshold value indicated in Annex III of the regulation.
Similarly, some other cases of combination are not relevant, this is when one of the criteria

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[a]: $\frac{14!}{(14-2)!\cdot 2!} = 91$

is already accounted for in the definition of the other combined criterion. For example the interaction of excess soil moisture with texture is already embedded conceptually into the criterion and taken into account in the calculation of the duration of field capacity days (soil hydraulic properties are related to soil texture). Consequently, the combination between *Excess soil moisture* and sub-criteria *texture – sand and loamy sand*, or *texture – heavy clay* have not been considered.
There is another case, when two criteria are conceptually linked, e.g. *Excess soil moisture* and *Limited soil drainage*, as these two criteria address the duration of soil wetness and consequently their combination should not be considered.

iv. Unclear synergy: when both positive and negative synergies are detected, and/or when the outcome of the combination depends on external factors which are not known (e.g. south/north facing slope) or which can act differently according to the specific situation (e.g. different outcome under a drier or wetter climate) or crop grown (i.e. different effect according to the species that is cultivated). In this case, flexibility is left to MS to demonstrate their cases (see section 2.2).
v. Combination not occurring: indeed not all possible combinations of the 14 biophysical (sub) criteria can occur physically in Europe or are possible from an agronomic and/or pedological and/or climatic point of view. For example, the *Dryness* and *Excess soil moisture* criteria, as defined in Annex III of regulation (EU) No 1305/2013, are most unlikely to occur at the same location. This is also the case for combinations involving the criterion *texture clay with vertic properties* (see vi. below on criterion *clay soil with vertic properties*), or criterion *Limited soil drainage* (see vi. below).

Moreover, the group of experts has identified specific cases where criteria combinations are not appropriate. This is for:

vi. Criterion *clay soil with vertic properties within 1 m soil depth.* It should be used in combination because a sub-severe threshold level cannot be identified as otherwise the inherent nature of the constraint (vertic properties) would be lost.
Similarly, criterion *Limited soil drainage* cannot be used in combination as the expert panel agreed that its thresholds should not be relaxed (see detailed justifications in section 2.2 below).

2.2 Establishing sub-severe level thresholds

In order to respond to the possibility of combining biophysical criteria of Annex III introduced by the legislator, initial work of the expert panel was to review each of the thresholds (within the margin of 20% of their initial value) and to explore advisable options for combining biophysical criteria within the legal framework. This analytical work has led to possible limiting criteria combinations and margins for the thresholds. The scientifically supported outcomes of this study provide a set of good practices for combining biophysical criteria which can support the mandate of the Commission to assess MS delineation. Consequently, MS are also encouraged to follow these guidelines; however it should be acknowledged that particular / local conditions can occur and flexibility is left to MS to demonstrate their cases with convincing scientific evidence for combinations labelled ‘unclear’ in the present report.

It should be kept in mind that the pairwise relaxation of the severe thresholds is relevant only when the two factors are both in the range between severe and sub-severe values, and at the same time the interaction is negative in terms of influence on agricultural production.

This assessment brought forward five cases:

i. The application of the 20% margin value to the initial threshold is plausible and feasible. The new sub-severe threshold is proposed.
ii. The assessment has also identified cases where the sub-severe threshold limit should be less than the 20% level of the original value (within a margin of 20%) to imply a constraint to agriculture. This is the case when interaction results in a severe constraint to agriculture but not anymore at the 20% limit value (e.g. for combinations involving the Low temperature criterion). In this situation a justification is provided for lowering the 20% margin. The other example is when a purely arithmetic (linear) margin of 20% is not appropriate (when criteria are not linear, e.g. soil acidity).
iii. In other cases it is proposed to keep the nature of the constraint (because of its qualitative property) but to relax only its quantitative expression (e.g. the new sub-severe threshold for sand and loamy sand [qualitative characteristics] would correspond to sand, loamy sand in 40% or more [quantitative value] of 1m soil layer, rather than half [50%] as originally indicated in Annex III).
iv. The strict application of the 20% margin from the initial threshold value is not advisable in cases when data of sufficient accuracy cannot be used at Member State level. Indeed some soil attribute values are based on expert assessment or are formatted to be consistent with international standards and are therefore rounded values. This should apply to e.g. criterion Shallow rooting depth (36 cm is not a commonly used value to define 'shallow' soils in most international and national soil classifications), to heavy clay content, and to organic soil layer extension.
v. The thresholds are not recommended to be relaxed (e.g. clay soil with vertic properties) as otherwise the nature of the constraint itself would be lost (e.g. a soil is considered 'vertic' or 'not vertic', there is no degree of 'vertic' characteristics).

The result of the expert group analysis in terms of shifting the threshold by 20 % or less is described below for each biophysical criterion.

Low temperature

The rationale for the low temperature threshold is an insufficient thermal-time accumulation during the crop growing period, hampering normal vegetation growth and/or preventing completeness of the crop cycle.

The severe threshold for the length of the growing period was initially set at 180 days; a 20% relaxation would correspond to 180 + 36 = 216 days (i.e. more than 7 months), which was judged to be no longer a severe constraint to agriculture even when combined with any other constraint. Therefore, it has been suggested to extend the minimum length of the growing period for the sub-severe threshold by only 15 days ($LGP_{t5} \leq 195\ d$), corresponding to two weeks during which crops could benefit from conducive temperatures (above 5°C) but during which field operations would be delayed by e.g. wet conditions (Rossiter and Van Orshoven, 2009). Following the same logic, it is proposed to increase the threshold for the thermal-time sum (initially 1500 degree-days) to 1575 degree-days ($TS_5 \leq 1575\ °C\ d$), corresponding to 15 days at an average daily temperature of 10°C with base temperature T_b = 5°C (15 d x 5°C = 75 °C d).

A full time series of meteorological data of at least 30 recent years (preferably a WMO international standard period, e.g. 1961-1990 or 1976-2005 or more recent) is required to assess the probability of occurrence of climate-related criteria at any location. The sub-severe threshold should be reached in more than 20% of the time (i.e. the constraint occurs in at least 7 years out of 30).

Dryness

The rationale for the dryness criterion is a natural permanent imbalance in the water availability for a normal rainfed crop. This imbalance consists of low total precipitation and high evapotranspiration demand, resulting in a low soil water content and low carrying capacity of the agro-ecosystem.

The 20% margin level from the initial threshold is proposed by the expert panel, leading to a sub-severe value for the ratio of annual total Precipitation (P) over annual total Potential Evapotranspiration (PET) below or equal to 0.6 ($P/PET \leq 0.6$). PET or reference evapotranspiration, should be computed using the Penman-Monteith methodology for a grass reference crop (Allen et al., 1998).

A full time series of meteorological data of at least 30 recent years (preferably a WMO international standard period, e.g. 1961-1990 or 1976-2005 or more recent) is required to assess the probability of occurrence at any location. The sub-severe threshold should be reached in more than 20% of the time (i.e. the constraint occurs in at least 7 years out of 30).

Excess soil moisture

The rationale for the excess soil moisture criterion is when the water content in the soil exceeds field capacity. This hampers field operations (workability, trafficability) and generates adverse effects on crop growth (reduced uptake of nutrients, pathogen development, and root injuries due to anoxic conditions in the rhizosphere).

The strict application of the 20% margin to the Field Capacity Duration (FCD) of more than 230 days would result in sub-severe threshold value of $FCD \geq 184$ *days* (i.e. 6 months). This value was judged by the expert panel to be too lenient to constitute a severe agricultural constraint when combined with any other criterion. A meaningful sub-severe threshold for the duration of field capacity (FCD) is therefore proposed to last at least 210 days (7 months).

The sub-severe threshold should be reached in more than 20% of the time (i.e. the constraint occurs in at least 7 years out of 30).

Limited soil drainage

The rationale for the limited soil drainage criterion is very similar to the one for excess soil moisture, being the effect of a reduction in the amount or lack of oxygen in the rooting zone, arresting plant growth, preventing nutrient uptake, increasing the incidence of soil-borne pathogens, and preventing tillage without severe damage to soil structure.

The Annex III threshold for this criterion has three possibilities:

i. water regime that is wet within 80 cm from the soil surface for over six months or wet within 40 cm for over eleven months (as defined by Daroussin et al., 1995);
ii. poorly drained (as defined by Soil Survey Division Staff, 1993);

iii. presence of gleyic colour pattern within 40 cm (as defined by IUSS Working Group WRB, 2006).

The expert panel agreed that easing the poorly drained criterion to the next class (i.e. somewhat poorly drained or imperfectly drained) would not be a severe constraint to agriculture for any of the possible combinations. Moreover, redefining a relaxed limit for the gleyic colour pattern was not considered advisable.

The definition of the water regime (WR) 'Wet within 80 cm for over six months' covers a wide range of wetness conditions, ranging from indeed 'too wet for agricultural use' to sometimes limited wetness, depending on the duration of wetness at shallow soil depth. For example, this class can have soils which are wet within 80 cm during six months (e.g. between 40 and 80 cm between 1 October and 1 April), and in the other six months it is wet below 80 cm (e.g. groundwater level (or saturated zone) moves down to 120 cm and up to 80 cm again). Such soils would have little wetness limitations for cropping (especially within 40 cm soil depth during the growing season).

Another situation that meets this ANC criterion is a soil with a constant groundwater level of 70 cm throughout the whole year, which would not constitute a significant wetness limitation either.

The reason that the scale of duration of waterlogging is too coarse (expressed in months) in most national and international soil classification systems is because of the paucity of soil dipwell data.

Because the wide range of possible wetness conditions defined by the water regime class, many soils will be defined in between the wettest and driest situation. Consequently, it is proposed not to relax the water regime threshold 'wet within 80cm from the soil surface for over six months or wet within 40cm for over eleven months'.

Unfavourable texture and stoniness

The rationale for this criterion is related to water-holding capacity and nutrient supply. Furthermore, texture affects workability and trafficability, water infiltration, run-off and water movement within the soil.

There are five sub-criteria for unfavourable texture, some of which apply to topsoil.

To guide implementation, the expert panel suggests adopting the following definition of topsoil:

Topsoil: Upper part of a natural soil that is generally dark coloured and has a higher content of organic matter and nutrients when compared to the (mineral) horizons below, excluding the humus layer. This definition is based on ISO 11074 (Jones et al., 2008) and for arable land refers to the tilled soil depth (i.e. 25-30 cm); and for grassland to the soil layer with high root content.

The following sub-severe thresholds were suggested when criteria are used in combination:

i. For topsoil with stones (15% of topsoil volume is coarse material, rock outcrop, boulder), the 20% margin value would mean a sub-severe threshold of 'more than 12% of topsoil volume is coarse material'. However, such detailed accuracy is not available in soil databases as stoniness cannot be realistically estimated in the field to better than plus or minus 5% and there is still likely to be significant errors. A pragmatic and applicable approach would be to use the nearest rounded value, i.e. more than 10% of topsoil volume is coarse material, including rock outcrop, boulder (coarse material definition FAO, 2006).

ii. For 'Texture class in half of the soil in a profile of 100 cm vertical depth is sand, loamy sand', the experts agreed that easing the texture class to 'sandy loam' would not constitute a limitation as sandy loam soils can be very productive. Consequently, no change is proposed to the qualitative description of the constraint (sand, loamy sand) but to the quantitative presence requirement (reduced to 40% within a 1 m depth as opposed to 50% originally). The sub-severe threshold would then be: Texture class in 40% or more (cumulatively) of the soil profile of 100 cm vertical depth is sand, loamy sand defined as Silt% + (2 x Clay%) ≤ 30%.

iii. For 'Topsoil texture class heavy clay (≥ 60% clay)', the theoretical 20% margin is ≥ 48% clay. However, it is unlikely that MS soil databases hold such detailed information on clay content and no repeated sampling would be accurate to better than plus or minus 2%. Consequently, it is suggested to use the rounded value of 50%. Hence the new sub-severe threshold would be: Topsoil texture has clay content of 50% (or more). This is acceptable because a topsoil with ≥ 50% clay constitutes a heavy textured soil that would have constraints for agriculture when combined with other limiting conditions.

iv. For organic soil, defined as having 'Organic matter ≥ 30% of at least 40 cm, either extending down from the surface or taken cumulatively within 100 cm of the soil surface', a threshold relaxation is difficult. A complicating factor is that, while soil layers with more than 30% organic matter are always considered as organic layers, soil layers containing 20 to 30% organic matter may not qualify as organic anymore, depending notably on clay content in the mineral fraction of these layers. Lowering the extension of the organic soil from 40 cm to 32 cm (20% margin) is again not appropriate because most MS' soil databases do not have so detailed information (centimetric divisions) on the thickness of the organic layer that would be accurate enough to make this distinction. Consequently, it is suggested for the sub-severe threshold to consider soils with organic matter ≥ 30% of at least 30 cm (thus rounding 32 cm to 30 cm), either extending down from the surface or taken cumulatively within 100 cm of the soil surface'.

v. For 'Topsoil with 30% or more clay and presence of vertic properties within 100 cm of the soil surface': as vertic properties are found in Vertisols and all kinds of vertic intergrades (e.g. Vertic Luvisols), a sub-severe threshold level could not be identified without the inherent nature of the constraint (vertic properties) being lost. Consequently, it is proposed not to change the initial threshold value.

Shallow rooting depth

The rationale for this criterion is related to the volume of soil available for:

i. the physical anchorage of the rooting system,
ii. the provision/storage of nutrient and water,
iii. the possibility of mechanised tillage.

The straight 20% margin from the initial threshold of the maximum rootable depth would be 36 cm. However, Member States may face difficulties because soil depth data of sufficient accuracy to implement this combination are unlikely to exist (36 cm is not a commonly used value to define 'shallow' soils in most international and national soil classifications). Consequently, it is proposed to use the rounded value of 35 cm for the sub-severe threshold of *Shallow rooting depth* criterion.

Poor chemical properties

The rationale for this criterion is related to:

i. the difficulty crops may face to extract water from the soil pores,
ii. the limitation to plant growth due to toxic elements in soil,
iii. the vulnerability to waterlogging,
iv. the damage to soil structure (and consequently increase in risk of erosion),
v. the limited availability of nutrients for plants.

There are three sub-criteria for poor chemical properties. In absence of other valid alternatives, the expert panel suggested acceptance of the 20% margin value for salinity and sodicity, but with a warning that Member States soil databases may not have this level of detail.

The following sub-severe thresholds were proposed when criteria are used in combination:

i. Salinity ≥ 3.2 dS/m in topsoil
ii. Sodicity ≥ 4.8 ESP in half or more of the 100 cm soil surface

For soil acidity in topsoil, the expert panel had the following comments: Strictly speaking, pH being the negative decimal logarithmic value of hydrogen ion activity, the 20% margin value (from pH = 5) for the sub-severe threshold would be pH = 5.1. However, soil databases do not have such accurate information on acidity and the experts suggested the value of 5.5 (measured in H_2O) for the pH sub-severe threshold since most pH classifications in soil databases are (at most) in steps of 0.5. In this example, one can see the limitation of applying the 20% margin to a non-linear criterion.

Steep slope

The rationale for this criterion is related to difficulties for mechanisation and restricted opportunities for cropping. Steep slopes are often associated with shallow soils and intense runoff generation.

The 20% margin from the initial threshold was proposed by the expert panel. This leads to a sub-severe value for change of elevation with respect to planimetric distance to be reduced from ≥ 15% to ≥ 12%.

Table 1 provides a summary of the sub-severe thresholds proposed by the expert panel when pair-wise combinations of criteria result in a negative synergy.

Table 1: ANC criteria and thresholds from Regulation EU(1305)2013 and proposed sub-severe thresholds for pair-wise combinations of criteria that result in a negative synergy.

CRITERION	DEFINITION	THRESHOLD Regulation EU(1305)2013 – Annex III	Margin ≤ 20% of threshold value (value suggested by the expert group)
CLIMATE			
Low Temperature	Length of Growing Period Thermal-time sum (degree-days)	≤ 180 days ≤ 1500 degree-days	≤ 195 days ≤ 1575 degree-days
Dryness	Precipitation / Potential EvapoTranspiration	≤ 0.5	≤ 0.6
CLIMATE AND SOIL			
Excess Soil Moisture	Number of days at or above field capacity	≥ 230 days	≥ 210 days
SOIL			
Limited Soil Drainage	Areas which are water logged for a significant duration of the year	Wet 80cm > 6 months, or 40cm > 11 months Poorly or very poorly drained Gleyic colour pattern within 40cm	No change No change No change
Unfavourable Texture and Stoniness	Relative abundance of clay, silt, sand, organic matter (weight %) and coarse material (volumetric %) fractions	≥ 15% of topsoil volume is coarse material, rock outcrop, boulder Texture class in half or more (cumulatively) of the 100 cm soil surface is sand, loamy sand Topsoil texture class is heavy clay (≥ 60% clay) Organic soil (organic matter ≥30%) of at least 40cm Topsoil contains 30% or more clay and there are vertic properties within 100cm of the soil surface	≥ 10% of topsoil volume is coarse material, rock outcrop, boulder Sand, loamy sand in 40% or more within 100cm surface layer Topsoil texture ≥ 50% clay Organic matter ≥ 30%, of at least 30cm within 100cm surface layer No change
Shallow Rooting Depth	Depth (cm) from soil surface to coherent hard rock or hard pan	Rooting depth ≤ 30cm	Rooting depth ≤ 35cm
		Salinity ≥ 4 dS/m in topsoil	Salinity ≥ 3.2 dS/m in topsoil

Poor Chemical Properties	Presence of salts, exchangeable sodium, excessive acidity	Sodicity ≥ 6 ESP in half or more of the 100 cm surface layer	Sodicity ≥ 4.8 ESP in half or more of the 100 cm surface layer
		Soil Acidity Topsoil pH (H_20) ≤ 5	Topsoil pH (H_20) ≤ 5.5
TERRAIN			
Steep Slope	Change of elevation with respect to planimetric distance (%).	Slope ≥ 15%	Slope ≥ 12%

2.3 Assessing pair-wise combinations

Table 2 reports 25 combinations with negative and three with positive synergy. For 19 combinations, it is unlikely that both criteria occur at the same location (termed ‘not occurring’); 21 combinations were considered not possible because the sub-severe threshold could not be defined (or was scientifically questionable) for one of the criterion; for 18 combinations, no interaction between the two criteria was found (or interaction was already embedded in the concept of the criterion). Finally, 5 combinations were labelled with ‘unclear synergy’.

Only for combinations with acknowledged negative synergy, it is suggested that the area should be considered as exhibiting a severe natural constraint to agriculture when meeting the proposed sub-severe threshold limits indicated in Table 1. For all other cases, the original framework based on Liebig’s law of the minimum is proposed be continued, i.e. the criteria apply individually at the threshold value indicated in Annex III of the regulation. In case of unclear synergy, flexibility is left to MS to demonstrate their cases (see section 2.2).

Combinations with negative, positive or unclear synergy were subject to the elaboration of factsheets prepared by the expert panel. Obviously, no factsheets were prepared for combinations with no interaction, for combinations which are unlikely to occur, or for those which have no sub-severe thresholds.

The scientific recommendations in the report are without prejudice to the legal framework of Regulation 1305/2013.

Table 2: Assessment of pair-wise ANC criteria combinations.

	Dryness	Excess soil moisture	Limited Drainage	Stoniness	Texture Sand	Texture H Clay	Texture organic	Texture vertic	Rooting Depth	Salinity	Sodicity	pH	Slope
Low Temperature	0	-	#	0	0	-	-	#	0	X	X	0	0
Dryness		X	X #	-	-	-	X	#	-	-	-	X	-
Ex soil moisture			0 #	=	0	0	-	0 #	-	X	X	0	+
Limit Drainage				#	#	#	#	X #	#	#	#	#	#
Stoniness					-	=	+	#	-	X	X	0	-
Texture Sand						=	+	#	-	-	X	0	0
Texture H Clay							0	#	-	-	-	-	=
Texture organic								#	X	X	X	0	=
Texture vertic									#	#	#	#	#
Rooting Depth										-	-	0	-
Salinity											-	X	X
Sodicity												X	X
pH													0

X: not occurring

=: unclear synergy

#: sub-severe threshold not possible / not accepted

0: no interaction between criteria or interaction already embedded in criteria definition

+: positive synergy = 2 combined severe constraints result in no severe limitation

-: negative synergy (2 combined sub-severe constraints result in severe limitation

Table 3: Relevant pair-wise combinations and main author.

Criterion 1		Criterion 2		Synergy	Author
Criterion	Sub-criterion	Criterion	Sub-criterion		
Low temperature		Excess soil moisture		-	BJ
Low temperature		Unfav texture & sto	Heavy clay	-	KVD
Low temperature		Unfav texture & sto	Organic soil	-	KVD
Dryness		Unfav texture & sto	Stoniness	-	JVO
Dryness		Unfav texture & sto	Sand, loamy sand	-	JVO
Dryness		Unfav texture & sto	Heavy clay	-	KVD
Dryness		Rooting depth		-	RC
Dryness		Poor chemical prop	Salinity	-	RC
Dryness		Poor chemical prop	Sodicity	-	RC
Dryness		Slope		-	JVO
Excess soil moisture		Unfav texture & sto	Stoniness	=	BJ
Excess soil moisture		Unfav texture & sto	Organic soil	-	BJ
Excess soil moisture		Rooting depth		-	BJ
Excess soil moisture		Slope		+	BJ
Unfav texture & sto	Stoniness	Unfav texture & sto	Sand, loamy sand	-	JVO
Unfav texture & sto	Stoniness	Unfav texture & sto	Heavy clay	=	KVD
Unfav texture & sto	Stoniness	Unfav texture & sto	Organic soil	+	KVD
Unfav texture & sto	Stoniness	Rooting depth		-	BJ
Unfav texture & sto	Stoniness	Slope		-	JVO
Unfav texture & sto	Sand, loamy sand	Unfav texture & sto	Heavy clay	=	KVD
Unfav texture & sto	Sand, loamy sand	Unfav texture & sto	Organic soil	+	BJ
Unfav texture & sto	Sand, loamy sand	Rooting depth		-	RC
Unfav texture & sto	Sand, loamy sand	Poor chemical prop	Salinity	-	AH
Unfav texture & sto	Heavy clay	Rooting depth		-	KVD
Unfav texture & sto	Heavy clay	Poor chemical prop	Salinity	-	KVD
Unfav texture & sto	Heavy clay	Poor chemical prop	Sodicity	-	KVD
Unfav texture & sto	Heavy clay	Poor chemical prop	pH	-	KVD
Unfav texture & sto	Heavy clay	Slope		=	KVD
Unfav texture & sto	Organic soil	Slope		=	JVO
Rooting depth		Poor chemical prop	Salinity	-	RC
Rooting depth		Poor chemical prop	Sodicity	-	RC
Rooting depth		Slope		-	JVO
Poor chemical prop	Salinity	Poor chemical prop	Sodicity	-	AH

Abbreviations:
Unfav texture & sto: Unfavourable texture and stoniness
Poor chemical prop: Poor chemical properties
BJ: B Jones RC: R Confalonieri KVD: K Van Diepen JVO: J Van Orshoven AH: A Hagyo

3 Factsheets for pair-wise combinations

3.1 Negative synergies

A *negative synergy* occurs when for the combination, the two sub-severe thresholds (below those for the severe limitation of the individual criteria) result in a combined 'severe' limitation.

3.1.1 Low temperature × Excess soil moisture

Agronomic rationale for the limitation

Low temperature limits crop growth and development through the impact on important physiological processes such as photosynthesis and leaf appearance (Porter and Gawith, 1999), whereas excess soil moisture adversely affects crop growth by restricting rooting conditions and reducing soil strength for workability and trafficability (Earl, 1997; Thomasson and Jones, 1989). Temporal patterns in soil moisture conditions are influential drivers for land management. Soils are also prone to soil compaction if trafficked or cultivated under wet conditions (Herbin et al., 2011), damaging soil structure which can reduce agricultural productivity significantly in subsequent years.

It is suggested that the combination of *Low temperature* and *Excess soil moisture* (Jones and Thomasson, 1985) will impact negatively on agricultural activity (Thomasson and Jones, 1991) to a greater degree than either of these two criteria acting independently at sub-severe threshold levels.

Scientific rationale for the limitation

This negative impact would occur because soils that are saturated with water, or still at field capacity, dry out more slowly under low temperatures than under higher temperatures. This is because soil with water filled pores has a much larger specific heat than soil with air filled pores (water has a much higher density [1000 kg m^{-3} at 4°C] than air [1.269 kg m^{-3} at 5 C]) and there is less evaporation.

Cannell et al. (1985) found that after the start of waterlogging, the oxygen flux density decreased most rapidly nearer the soil surface and in the upper 50 cm declined to zero, severely restricting plant growth. The evapotranspiration of water from soil and through leaf surfaces is controlled by temperature and sunshine (see Penman and Monteith methodology as described by Allen et al., 1998), thus low temperature that alone suppresses plant growth *de facto*, would further lower the water loss through evapotranspirative processes, leading to soils remaining wet.

For oxygen availability and nutrient uptake, Trought and Drew (1982) reported that the concentration of dissolved oxygen declined rapidly at all temperatures, falling to zero after 36 hours waterlogging. Furthermore, Trought and Drew (1982) found that temperature affected rates of change in dissolved nitrate, calcium and potassium, confirmed by other research indicating that when soils are very wet, nutrient uptake reduces or even ceases altogether (Keane, 2001).

Sub-severe thresholds value for negative synergy

It is proposed that the combination of the sub-severe limitations for *Low temperature* and *Excess soil moisture* results in a severe overall rating.

- The *Low Temperature* threshold values (constraints) can be relaxed for thermal-time sum from less than 1500 to less than 1575°C-day and/or for length of growing period from less than 180 days to less than 195 days.
- The sub-severe *Excess soil moisture* threshold is suggested to be a field capacity duration equal or more than 210 days.

Likely conditions where it can occur

Areas that would most likely meet the relaxed (revised) threshold values for both criteria are largely confined to northern and north-western Europe.

3.1.2 Low temperature × Unfavourable texture and stoniness (heavy clay)

Agronomic rationale for the limitation

The *Low temperature* limitation means that the growing season is short, besides a long and cold winter depending on latitude and distance from the sea.

For crops planted in spring, late seeding due to cool or wet field conditions risk to make the period available for growth too short. Any delay in planting time implies a loss of production opportunities by shortening the effective growing season. Typical constraints of late maturity are interference of the harvest of spring crops with sowing of winter crops, and damage by early frost of late maturing crops and probably lower crop quality.

A heavy clay texture of the topsoil is directly related to plant nutrient supply, soil moisture conditions, rooting conditions, and ease of tillage (Thomasson and Jones, 1989; Van Orshoven et al., 2014; FAO, 1998). After the wet winter, in the spring, the moment when tillage and sowing is possible is later on clayey texture than on lighter textured soils, because the clays need more time for drying before good tillage conditions are reached. It makes the growing season even shorter. Often the seedbed becomes coarse structured and non-uniform and dries out quickly, which may cause poor crop emergence (Håkansson et al., 2002). Apart from the delay in tillage, the high moisture content of the heavy clay soils delays also their warming up in spring. In addition, ploughing heavy clay soils requires powerful machinery that is mainly heavy. The use of heavy machinery on clay soils may also create compaction, or a compacted layer, notably by traffic in a moment when the soil is still too wet. Compaction affects the rootability and aeration of the soil, and leads to lower crop yields.

Scientific rationale for the limitation

Heavy clays are difficult to cultivate, being sticky when wet and hard when dry. The optimum range for soil tillage lies between these two boundaries crucially related to soil moisture content and to soil structure (Mueller et al., 1990).

The soil moisture dynamics in heavy clay soils are in general slow and persistent, but where there is sufficient air-filled pore space, the wetting and drying can go relatively fast. Clays have many small pores, in which water is held under a high tension, and a large part of this water cannot be extracted by the plant roots. The process is controlled by capillary forces. A well-structured clay has also larger pores, and this water is more easily available (Bouma, 1981) but still holds at higher suctions than in sandy and coarse loamy soils.

Most heavy clay soils, especially when compacted, have very low permeability because the pores between the clay particles are narrow so that excess water ponds on the soil surface even after moderate rains rather than percolating downwards through the soil profile. Once a clay soil is wet, and nearly saturated with water, there is a risk of oxygen shortage in the root zone. After rainy periods, the soils may remain wet for a relatively long time, as internal drainage remains slow.

The negative interaction stems from the shortening of the effective growing season on heavy clay top soils in comparison with other soils. The soil requires more heat units than other soils, just for warming up and drying in order to reach suitable tillage and growing conditions. The higher energy requirements are related to the higher water content of the soil at the end of the winter, compared to other soils. Under a low temperature climatic regime, the available duration of the growing season is already a limitation, which is aggravated by the delaying influence of the heavy clay topsoil.

Sub-severe thresholds value for negative synergy

This negative interaction requires that for crop production on heavy clay topsoil the growing season needs a longer lead time, which can be translated into an extension of the minimum required duration of the growing season. The exact difference in duration depends on a number of climatic and site factors like the preceding winter conditions, temperature and rainfall, groundwater and landscape position, but it seems reasonable to extend the threshold with some 15 days, or its equivalent in sum of temperature (TS_5) and length of growing period (LGP_{t5}).

For LGP_{t5} this means a shift from equal or less than 180 days to equal or less than 195 days, and for TS_5 from equal or less than 1500 to equal or less than 1575 °C d.

To be effective, in case that the combination of *Low temperature* and *heavy clay* soil occurs, the clay content threshold may be reset down to 50% because soils with this amount of clay are classed as heavy textured over most of Europe (e.g. Pelosols contain more than 40% clay, Avery, 1974).

It means that

- The *Low Temperature* threshold values can be relaxed for thermal-time sum from less than 1500 to less than 1575°C-day and/or for length of growing period from less than 180 days to less than 195 days.
- The sub-severe threshold for *Unfavourable texture and stoniness (heavy clay)* is suggested to be 50%.

Likely conditions where it can occur

The low temperature zones occur in northern and north-western Europe. Heavy clay soils are found scattered in these regions.

3.1.3 Low temperature × Unfavourable texture and stoniness (organic soil)

Agronomic rationale for the limitation

Organic soils have low bulk density, limited physical stability and weak soil strength resulting in poor trafficability (Pietola et al., 2005). The bearing capacity of the soils is very small, especially during wet periods when organic soils are much more at risk of suffering severe structural damage by traffic (animals as well as machinery) than most mineral soils.

In areas characterised by low temperature, the growing season is short. If the period when temperature is high enough for crop development it can be further shortened by delay in the start of the cropping season due to the unfavourable soil conditions, reducing opportunities for agriculture. In most cases this constraint is further aggravated by poor drainage conditions while the options for improvement of internal soil drainage are limited.

In historical times, the peat layers were used for improving the soil profile, by mixing organic material with the mineral soil, thereby reducing mineralization and the gradual disappearance of the organic soil material. A special use is the extraction of the organic material in horticulture as a basis for potting composts. Currently, the emphasis of the soil management is on preserving the organic material (i.e. avoiding mineralisation by ceasing to cultivate organic soils). Due to the negative synergy of poor trafficability and shortened growing season, the organic soils in low temperature zones are unfavourable for mechanized agriculture hence preferably used for grazing.

Furthermore, when peat soils are used for arable crop production, they usually require artificial drainage which increases the oxygen content which subsequently leads to rapid mineralisation of the organic matter. Additions of lime and fertilizers, in order to permit cultivation of normal crops exacerbate the problem of organic matter oxidation. Under these circumstances, the drain depth needs to be kept as shallow as possible along with prudence exercised when applying lime and fertilizers to minimise the wastage of the peat (Renger et al., 2002; Jones et al., 2004).

Scientific rationale for the limitation

Organic soils are associated either with low temperatures or poor drainage, or both (Driessen et al., 2001). The nature of the synergy (if it hinders or favours agricultural land use, i.e. negative or unclear) between the two criteria at sub-severe thresholds level depends on the quality of the organic material, but mainly negative.

Soil strength depends directly on soil bulk density which in turn depends on granulometry and organic matter content (van den Akker, 2004; Imhoff et al., 2004). The loose structure and flexible peat fibres play a role here (Driessen et al., 2001). Organic soils have low bulk densities (0.2-0.8 t m^{-3}; Hammond and Brennan, 2003) which are much lower than the bulk densities of sandy and loamy soils (1.3-1.6 t m^{-3}; Hall et al., 1977). Consequently, the bearing strength of organic soil is much less than that of sandy and loamy soils which greatly reduces opportunities for undertaking mechanical field operations.

Sub-severe thresholds value for negative synergy

The combined occurrence of *Low temperature* and *organic soils* can generally lead to a worsening of the opportunities for agricultural use. To account for the negative synergy, it is proposed to accept the two limitations at the sub-severe thresholds.

- The sub-severe threshold can be defined as *organic soil* with organic matter (≥ 30%) of 30 cm or more, either extending down from the surface or taken cumulatively within the upper 100 cm of the soil.
- The *Low temperature* limitation can be relaxed by extending the threshold with some 15 days, or its equivalent in TS_5 and LGP_{t5}. For LGP_{t5} this means a shift from equal or less than 180 days to equal or less than 195 days, and for TS_5 from equal or less than 1500 to equal or less than 1575 degree-days.

Likely conditions where it can occur

The low temperature zones occur in northern and north-western Europe. Relevant for the evaluation of the combined interaction are areas located south of the 62nd latitude parallel, where organic soils occur extensively (Montanarella et al., 2006). In the most humid areas, the upland landscape may be covered by relatively shallow 'blanket peat' overlying hard rock, while locally a thicker peat mass can be found. Elsewhere, organic soils are confined to lowland areas, poorly drained basins and depressions, swamps and marshlands with shallow groundwater.

3.1.4 Dryness × Unfavourable texture and stoniness (stoniness)

Agronomic rationale for the limitation

Dryness and *stoniness* in combination have been selected to reflect the requirements for water, stability and oxygen in the root zone of an average crop in Europe.

In areas characterised by low precipitation compared to potential evapotranspiration, the growing season is short due to early exhaustion of the plant available soil water, at the start of the growing season, through evaporation of water from the soil surface and transpiration from crop plants.

Apart from reducing the volume of soil able to hold water and supply nutrients especially in areas with pronounced dryness, large amounts of coarse material > 2 mm (Hodgson, 1978) in the topsoil can damage/wear cultivation machinery.

Scientific rationale for the limitation

In a stony topsoil the volume of fine earth (< 2 mm esd) for storage of water will be significantly below that for average soils, which points to a negative synergy between the two limitations.

However, a stony topsoil will limit the upward movement of water by capillary rise from the underlying layers so that loss of water by soil evaporation is reduced (Kosmas et al., 1994). This latter aspect is however less important than the further reduction of the soil available water, resulting eventually in a negative synergy.

Sub-severe thresholds value for negative synergy

The proposed sub-severe thresholds are applied here.

- The sub-severe threshold for *Dryness* is suggested as P/PET ≤ 0.6 where P is the annual precipitation and PET is the annual potential evapotranspiration, both expressed in the same unit (UNEP Aridity Index). It should be reached in more than 20% of the time (i.e. the constraint occurs in at least 7 years out of 30).
- The sub-severe threshold for *Unfavourable texture and stoniness (stoniness)* is suggested as: volume of coarse fragments of any kind in topsoil is more than 10% (including rock outcrops and boulders).

Likely conditions where it can occur

In southern Europe there are important areas which experience both dry conditions and stony topsoils. Such land is typically restricted to perennial crops like olive trees and vineyards.

3.1.5 Dryness × Unfavourable texture and stoniness (sand, loamy sand)

Agronomic rationale for the limitation

In areas characterised by low precipitation compared to potential evapotranspiration, the growing season is short due to early exhaustion of the plant available soil water, at the start of the growing season, through evaporation of water from the soil surface and transpiration from crop plants. In a soil profile in which the soil texture is sand or loamy sand in 40% or more (cumulatively of the soil profile of 100 cm vertical depth), water holding capacity will be below average, so that exhaustion of the available soil water at the beginning of the growing season is likely to be accelerated. This points to a negative synergy between the two limitations.

Scientific rationale for the limitation

The interaction between meteorological conditions and soil texture has been intensively studied by means of mechanistic crop-soil water balance models based on the Richard's equation. These models and studies (e.g. Belmans et al., 1983) revealed that precipitation deficit leads to more pronounced crop transpiration deficit in soils with low available water capacity and high hydraulic conductivity (like sandy soils) compared to other soils.

It is important to emphasise that the Dryness criterion is assessed on an annual basis while pronounced variability of P/PET may be present throughout the year.

Sub-severe thresholds value for negative synergy

A sandy soil requires relatively more precipitation with respect to the potential evapotranspiration compared to finer textured soils in order to meet the crop water requirements adequately. A relaxation of the threshold to 60% P/PET, in line with the 20% margin of the original threshold, seems reasonable.

- The sub-severe threshold for *Dryness* is suggested as P/PET ≤ 0.6 where P is the annual precipitation and PET is the annual potential evapotranspiration, both expressed in the same unit (UNEP Aridity Index). It should be reached in more than 20% of the time (i.e. the constraint occurs in at least 7 years out of 30).

It is justifiable to also relax the threshold for the sandy nature of the soil to, e.g. 40% rather than 50% of the total depth.

- The sub-severe threshold for *Unfavourable texture and stoniness (sand, loamy sand)* is thus proposed as: Texture class (fine earth particle < 2 mm) in 40% or more (cumulatively) of the 100 cm soil surface is sand, loamy sand (defined as Silt% + 2 x·Clay% ≤ 30%).

Likely conditions where it can occur

Areas with sandy soils which experience an aridity index of P/PET ≤ 0.6 occur mainly in the Mediterranean areas of southern Europe and in Central Europe.

3.1.6 Dryness × Unfavourable texture and stoniness (heavy clay)

Agronomic rationale for the limitation

In semi-arid zones of Europe, with aridity index below 0.5 (Kosmas et al., 1999), rainfed agriculture relies heavily on winter and spring rainfall. The warm and usually very dry summers are characterised by average crop and pasture yields below European standards.

To avoid summer drought as much as possible, and to take maximum benefit of winter precipitations, it is important that crops are sown as early as possible. The cropping strategy should be to complete the crop cycle as early as possible, while ensuring maximum and efficient use (for transpiration) of the available water. However, heavy clay soils have a narrow time window for soil tillage, and even in dry climates the soil may be too wet for ploughing which aggravates the limitation for agricultural use (Mueller et al., 1990).

Also, during the growing season, when the soil moisture reserves have been depleted, the soil may dry out below wilting point, so that the crop will not benefit from an occasional rain shower anymore. Consequently, the risk of low yield and even crop failure is higher in dry areas on heavy clay topsoil than on most other soil types.

The *Dryness* limitation requires good management to make maximum use of the scarce water resources and to allow the crop to complete its growth cycle in time, before the drought becomes persistent. This task is difficult to achieve on farm fields with heavy clay topsoil, as compared to fields with finer soil textures (Kimble, 1990), as all required activities are negatively influenced by the characteristics of heavy clay texture.

In summary, dryness leads to short growing seasons due to the lack of soil moisture, and heavy clay topsoil leads to a further shortening of this effective growing season. This points to a negative synergy between the two limitations.

Scientific rationale for the limitation

Water scarcity is the main limitation in the semi-arid zones in Europe which, through its seasonal pattern, leads to a short effective growing season. In a dry heavy clay topsoil, the development of a root system is hampered. Drought limits the possibility of crop plants to transpire and this affects the uptake of nutrients and photosynthesis and, as the cooling function of transpiration stagnates, it leads to higher internal temperatures and accelerated senescence of the plants. In this way summer drought aggravates the negative effects of high temperatures.

In comparison with other textures, soils with heavy clay texture are hard to labour, the time available for tillage operations is short, they are sensitive to compaction, and they continue to evaporate. Crops have a less finely distributed rooting system and more problems to extract the available moisture from the soil matrix (IUSS Working Group WRB, 2006). In case the soils are situated on a slope, runoff could lead to water losses, and when situated in flat terrain, surface water ponding could happen easily. This variation of alternating periods of wetness and drought, typically for heavy clay topsoils in semi-arid regions is sometimes referred to as extreme water regime (Varallyay, 2009), attributed to the low water infiltration capacity, irregular rainfall regime and spatially variable (micro)relief. It is also an expression of the negative synergy between the two combined limitations.

Sub-severe thresholds value for negative synergy

Given the negative interaction between the dryness limitation and a topsoil of heavy clay it seems reasonable to relax the threshold values to account for the negative synergy.

- This implies a shift in the threshold value of topsoil clay content to a less heavy clay, i.e. dominant texture class of topsoil is heavy clay defined with clay content ≥ 50% in combination with a reduction in the UNEP Aridity Index to a less dry climate;
- The sub-severe threshold for *Dryness* is suggested as P/PET ≤ 0.6 where P is the annual precipitation and PET is the annual potential evapotranspiration, both expressed in the same unit (UNEP Aridity Index). It should be reached in more than 20% of the time (i.e. the constraint occurs in at least 7 years out of 30).

Likely conditions where it can occur

Semi-arid climates are found in the Mediterranean and in Central Europe, with the largest extents in the Iberian Peninsula and in the Danube Basin. Soils with heavy clay topsoil are found scattered in these regions.

3.1.7 Dryness × Shallow rooting depth

Agronomic rationale for the limitation

A well-developed and deep rooting system is a key precondition for plants to adapt to environmental conditions and to support high production levels. In this context, a shallow soil often represents a limiting factor for agricultural activities, because of the increased susceptibility to compaction (Bullock and Houérou, 1996) and of the reduced capability to store nutrients and water, that could represent a severe constraint in case of dry spells (Sadras and Calviño, 2001). Compacted, shallow and dry soils could severely decrease nutrients and oxygen mobility in the layers explored by roots, with a negative impact on root and shoot growth (Jensen et al., 2003; Pagliai et al., 2004).

Scientific rationale for the limitation

The ability of roots to expand into the soil is a key factor for plant growth and development, since it is directly related to the nutritional status of the plant and to the capability of the plant to adapt to a changing environment. A well-developed rooting system allows reducing the susceptibility to lodging (Clark et al., 2003), facilitates the access to nutrients and water, and increases the capability of the plant to compete against other species (Place et al., 2008). The volume of soil that can be explored by roots can be limited by the presence of physical (e.g. rocks) or chemical barriers (e.g. high concentration of toxic elements, agrochemical residues or low pH) (Lefroy and Stirzaker, 1999).

Especially in shallow soils, extreme drought conditions could result in a marked decline in soil organic matter content and microbial activity, severely compromising the function, structure and productivity of the soil layers where roots can grow (Geng et al., 2014). The resulting losses in soil aggregate stability can frequently lead to sealing and encrustation of surface layers and to high subsoil compaction, lowering infiltration rates and increasing the risk of runoff and erosion (Bullock and Houérou, 1996). Under such conditions, the progressive rise in soil strength (penetration resistance) can reach values around 2 MPa at 30 cm depth during spring and summer months (Figure 1), further reducing the soil volume accessible to roots (Gregory et al., 2007).

The presence of physical barriers to axial root growth promotes both morphological and functional modifications. The first involves the reduction of root hair density and the increase in root diameter (Dodd, 2007), the second adversely affects the plant's capability to uptake water and nutrients (Scott et al., 2005). For some herbaceous species (e.g. sunflower and maize), short and thick roots can have positive effects on resistance to lodging (Goodman and Ennos, 1999), but when severe drought conditions occur, negative impacts on crop growth and development prevail (Tracy et al., 2011). In the light of these considerations, shallow soils in a dry environment should be considered as fragile and susceptible to land degradation (Geng et al., 2014).

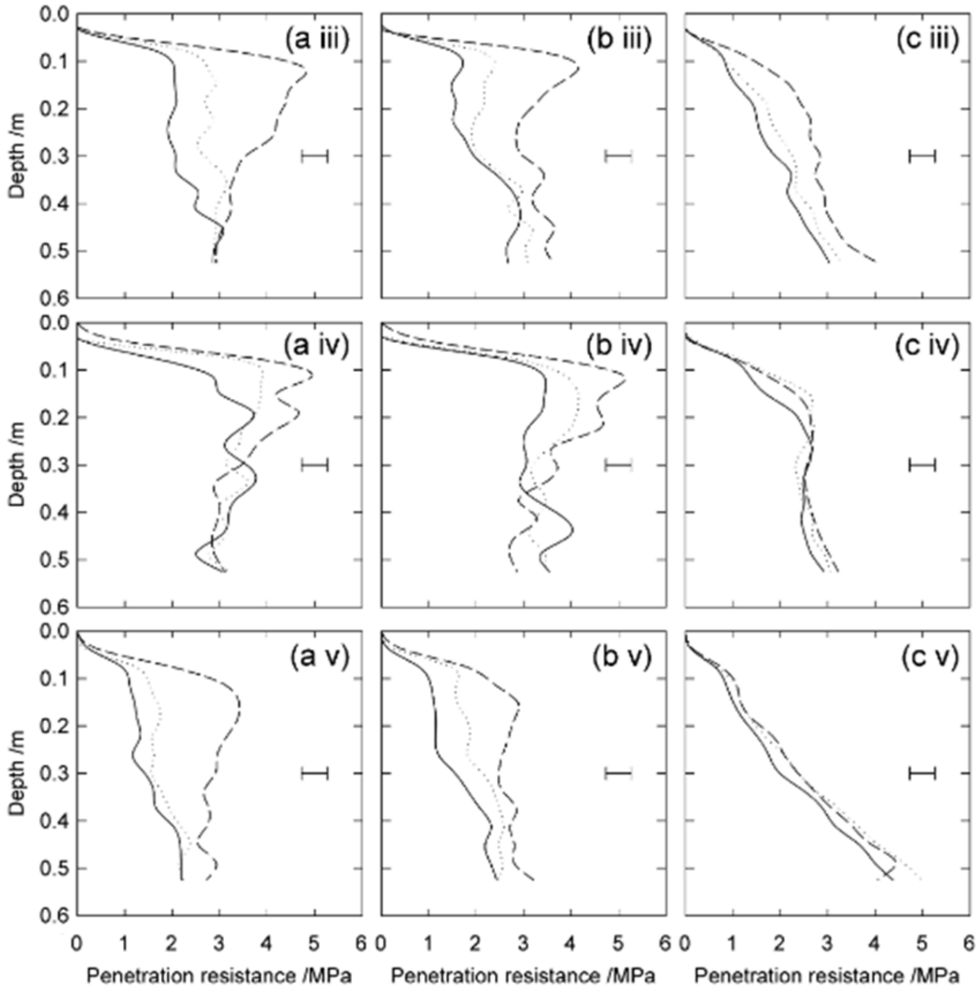

Figure 1: Penetration resistance measured in sandy loam (a), sandy clay (b), and clay soil (c), in May (iii), June (iv), and September (v). Uncompact soil (continuous line), lightly-compacted (dotted line), heavily-compacted (dashed line) are respectively shown (Source: Gregory et al., 2007).

Sub-severe thresholds value for negative synergy

According to what has been discussed in the previous sections, a negative interaction is considered. A shallow soil has to receive more precipitation as compared to the potential evapotranspiration in order to better meet crop water requirements. A relaxation of the threshold to 60% P/PET (with annual rainfall P and potential evapotranspiration PET, the latter calculated according to the Penman-Monteith methodology), in line with the 20% margin of the original threshold, seems reasonable.

- The sub-severe threshold for *Dryness* is suggested as P/PET ≤ 0.6 where P is the annual precipitation and PET is the annual potential evapotranspiration, both expressed in the same unit (UNEP Aridity Index). It should be reached in more than 20% of the time (i.e. the constraint occurs in at least 7 years out of 30).
- The sub-severe threshold for *Shallow rooting depth* is assumed to be ≤ 35 cm.

Likely conditions where it can occur

Shallow soils under semi-arid conditions are found sporadically in the Mediterranean region and elsewhere in southern, central and eastern Europe.

3.1.8 Dryness × Poor chemical properties (salinity)

Agronomic rationale for the limitation

Soil salinity is one of the major environmental constraints to agriculture worldwide (Pitman et al., 2002), especially in arid and semi-arid areas where dry climate exacerbates the negative effects of salt stress on crop productivity. The resulting stress can markedly restrict soil suitability to agricultural land-use even in regions where climatic conditions would be – *per se* – suitable for rainfed agriculture. Moreover, dryness-driven evaporation from topsoil could result in high salt loading on the soil surface, which may significantly increase the negative effect of salinity on crop emergence and seedling growth (Abrol et al., 1988; Läuchli and Grattan, 2000).

Scientific rationale for the limitation

The negative interaction between salinity and dryness may affects the plant-soil system in a variety of ways.

In saline soils, the low osmotic potential of the soil solution increases the minimum strength that must be overcome to extract water from soil pores. Prolonged drought conditions and high salinity levels also lead to ion imbalance and deficiency in the plant nutrient uptake, because of the competing effect of toxic ions on nutrient absorption from the substrate solution.

The primary effect of salinity is the reduction of plant water uptake that leads to moisture even when water is still present in the rhizosphere (Ayers and Westcot, 1994; Hasegawa et al., 2000; Munns, 2002; Rengasamy, 2006; Castillo et al., 2007; Taiz and Zeiger, 2009). The principle behind this phenomenon is well illustrated in Figure 2, which presents the variations in soil water availability as a function of total soil water potential, taking into account the osmotic effect due to different levels of soil salinity. In order to withdraw water from a salty soil solution, the plant must overcome a force that is directly related with salt concentration.

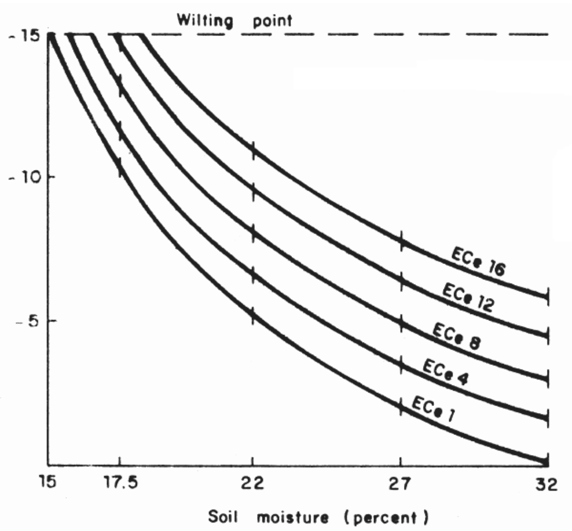

Figure 2: Theoretical available soil water as influenced by average soil water salinity (ECedS/m) for a clay-loam soil. On x-axis soil water content (%) is reported, whereas on y-

axis total soil water potential is represented (bar); 0 = water holding capacity; -15 = wilting point (Source: Ayers and Westcot, 1994).

Under dry conditions, water loss driven by high evapotranspirative demand produces an increase in salt concentration in the soil solution, which results in a more negative soil water potential. This directly causes low transpiration rates, affects ion active transport and membrane permeability, leading to reduced nutrient absorption and transport from roots to shoots. In such a context, salinity also contributes to alter the nutritional status of plants, by limiting the absorption of Ca^{2+}, K^+ and Mg^{2+} ions via both physiological inactivation and competition effects, which in turn lower the ability of plants to selectively adsorb a given nutrient in case of high concentration of Na^+ and Cl^- in the soil solution (Grattan and Grieve, 1999; Taiz and Zeiger, 2006).

Sub-severe thresholds value for negative synergy

A saline soil needs to receive more precipitation, as compared to the potential evapotranspiration, in order to better meet crop water requirements. A relaxation of the threshold for P/PET, in line with the 20% margin of the original threshold, seems reasonable.

- The sub-severe threshold for *Dryness* is suggested as P/PET ≤ 0.6 where P is the annual precipitation and PET is the annual potential evapotranspiration, both expressed in the same unit (UNEP Aridity Index). It should be reached in more than 20% of the time (i.e. the constraint occurs in at least 7 years out of 30).
- The sub-severe threshold for *salinity* is ≥ 3.2 dS/m in topsoil.

Likely conditions where it can occur

Semi-arid conditions in combination with salinity are found sporadically in river deltas and on coastal plains in the Mediterranean and in occasionally on plains of the Danube basin.

Salt accumulation from shallow groundwater is typical for arid and semi-arid climates in low-lying plains. Salt can also be brought by flooding with sea water or slightly saline river water, or by runoff from surrounding sloping land.

3.1.9 Dryness × Poor chemical properties (sodicity)

Agronomic rationale for the limitation

Water holding capacity is a crucial property of agricultural soils, especially in regions where water supply strictly depends on rainfall, such as arid and semi-arid environments. In this context, sodicity-affected soils present unfavourable characteristics, because of their lack of structure, which may further worsen water limiting conditions in case of prolonged drought periods. Moreover, in dry lands, sodic soils are often affected by severe seedling emergence failure due to surface crust formation that may increase soil exposure to run-off and erosion.

Scientific rationale for the limitation

The increase in exchangeable sodium percentage (ESP) is one of the most common causes of soil structural degradation. High sodium concentration causes both soil dispersion and aggregate swelling that can lead to soil structural alteration, thus affecting water holding capacity (Qadir and Schubert, 2002; Bronik, 2004; Hanson et al., 2006). Indeed, drainage and water redistribution within the soil profile becomes slow and scarce (Rengasamy et al., 2003), as a consequence of the reduced infiltration rate (Brouwer et al., 1988) and hydraulic conductivity (Abrol et al., 1988). The reduction of water infiltration in sodic soils is also due to the physico-chemical dispersion of clay particles, which in turn causes both clogging and sealing of soil pores with risk of runoff events (Abrol et al., 1988; Hillel, 2000; Qadir and Schubert, 2002). The effect of ESP on the infiltration rate as a function of cumulative rain is shown in Figure 3.

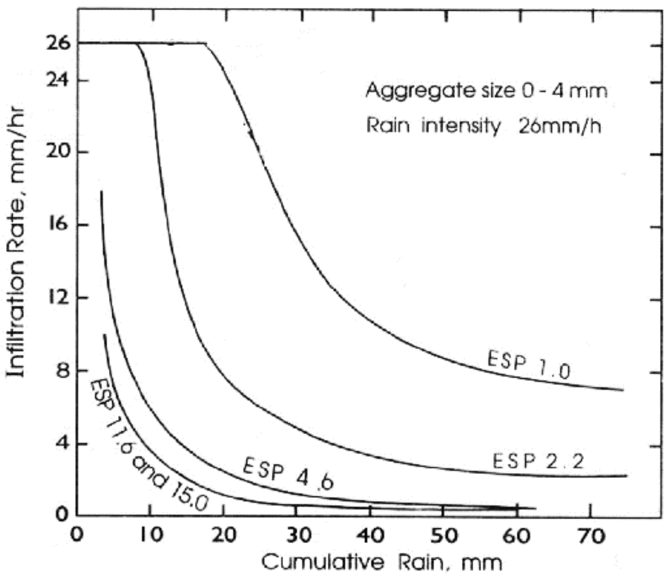

Figure 3: Effect of different ESP values on the infiltration rate of a sandy loam soil as a function of cumulative rainfall, artificially reproduced by using deionized water (Source: Kazman et al., 1983).

Surface crusting typically affects sodic soils, especially in arid and semi-arid regions (Chhabra, 1996; Hillel et al., 2000; Qadir and Schubert, 2002). Dispersion of aggregates, indeed, causes structural degradation and, as the soil dries, the development of a non-structured cement-like layer on the surface which dramatically impairs seedling emergence (Hillel et al., 2000; Qadir and Schubert, 2002).

Sub-severe thresholds value for negative synergy

Areas with sodic soils must be characterized by a more favourable rainfall to potential evapotranspiration ratio to meet crop water requirements during the growing season. A relaxation of the threshold for P/PET, in line with the 20% margin of the original threshold, seems reasonable.

- The sub-severe threshold for *Dryness* is suggested as P/PET ≤ 0.6 where P is the annual precipitation and PET is the annual potential evapotranspiration, both expressed in the same unit (UNEP Aridity Index). It should be reached in more than 20% of the time (i.e. the constraint occurs in at least 7 years out of 30).
- Sub-severe threshold for *sodicity* is ≥ 4.8 ESP in half or more (cumulatively) of the 100 cm soil surface layer.

Likely conditions where it can occur

Semi-arid conditions in combination with sodicity are found sporadically in the Mediterranean and in occasionally in the Danube Basin.

3.1.10 Dryness × Steep slope

Agronomic rationale for the limitation

The combination of the *Dryness* and the S*teep slope* criteria and thresholds have been selected to reflect the requirements for water and physical stability of a crop and also for the difficulties for mechanisation in crop management.

The *Dryness* criterion is assessed without taking the landscape position into account (as this would require very detailed data and will differ from site to site). It is assumed that there is no net gain or loss of water from adjacent areas. However, steep upslope areas typically do not retain water because of gravity movement under gravity. This points to a negative synergy between dryness and steep slope.

Scientific rationale for the limitation

Slope as such has little or no direct influence on the yield of crops. However, the steeper the slope the more difficult it becomes to manage the land and the less opportunities farmers have to grow crops. Steeper slopes are also associated with shallower soils in general, less water retention capacity due to gravity and a higher risk of soil degradation (erosion) and landslides.

The tendency of a landscape position to shed or accumulate surface water (not taking into account groundwater) is better measured by the Topographic Wetness Index (Beven and Kirby, 1979), which takes into account upslope contributing area as well as slope. This cannot be assessed by the dryness criterion as defined here. Yet, in general steeper slopes tend to occur in higher landscape positions (Rossiter and Van Orshoven, 2009) and lead to more pronounced 'apparent dryness'.

Sub-severe thresholds value for negative synergy

It is proposed that a combination of the following sub-severe thresholds for dryness and steep slope criteria leads to an overall 'severe' rating. The sub-severe thresholds are based on the 20% margin.

- The sub-severe threshold for *Dryness* is suggested as $P/PET \leq 0.6$ where P is the annual precipitation and PET is the annual potential evapotranspiration, both expressed in the same unit (UNEP Aridity Index). It should be reached in more than 20% of the time (i.e. the constraint occurs in at least 7 years out of 30).
- *Steep slope*: slope gradient larger or equal to 12% may cause limitations. Not so much for mechanisation but through the exacerbated loss of water stored in the soil due to run-off in an already dry region.

This proposal should be treated with caution, as sloping areas can be areas of water accumulation (concave foot slopes) rather than sources of water. It also depends on the distribution and intensity of rains contributing to dryness. If they are regular and well-spaced, there will be little runoff. However, in Mediterranean hilly areas much of the moisture may come from irregular heavy rains, leading to soil saturation, reduced infiltration and runoff, thereby reducing moisture storage (Rossiter and Van Orshoven, 2009).

Likely conditions where it can occur

Zones with this combination are widespread in Mediterranean hilly areas.

3.1.11 Excess soil moisture × Unfavourable texture and stoniness (organic soil)

Agronomic rationale for the limitation

Excess soil moisture (Jones and Thomasson, 1985) results from inadequate soil drainage, a high water table, seepage or runoff from surrounding areas, which adversely affect crop growth by restricting rooting conditions (Cannell et al., 1985) and reducing soil strength for workability and trafficability (Thomasson and Jones, 1989; Earl, 1997). These effects are exacerbated in areas of high rainfall (>1000 mm annually). Temporal patterns in soil moisture conditions are influential drivers for land management.

Organic soils have low bulk density, limited physical stability and weak soil strength resulting in poor trafficability. The bearing capacity of these soils is therefore very small, especially during wet periods when organic soils are much more at risk of suffering severe structural damage by traffic (animals as well as machinery) than most mineral soils. When dry, the bearing capacity remains low.

Scientific rationale for the limitation

Organic soils are associated primarily with poor drainage. Soil strength depends directly on soil bulk density, which in turn depends on granulometry and organic matter content (van den Akker, 2004). Organic soils have low bulk densities (0.2-0.8 t m^{-3}; Hammond and Brennan, 2003), which are much less than the bulk densities of sandy and loamy soils (1.3-1.6 t m^{-3}; Hall et al., 1977). Consequently, the bearing strength of organic soil is much less than that of sandy or loamy soils and hence, have very limited bearing capacity, which greatly reduces opportunities for undertaking mechanical field operations. In general, organic soils in combination with Excess Soil Moisture are unfavourable for mechanized agriculture.

When organic (peat) soils are used for arable crop production, they usually require artificial drainage, which increases the oxygen content leading to rapid mineralisation of the organic matter. Additions of lime and fertilizers, in order to permit cultivation of normal crops exacerbate the problem of organic matter oxidation. Under these circumstances, the drain depth needs to be kept as shallow as possible along with prudence exercised when applying lime and fertilizers to minimise the decomposition of the peat (Jones et al., 2004).

Therefore, the combination of *Excess soil moisture* and *Unfavourable texture and stoniness (organic soil)* will have strongly negative impacts on agricultural activity. However, a special use is the extraction of the organic soil material for use in horticulture as a basis for potting composts. Currently, in the management of organic soils there is increasing emphasis on preserving the organic material (i.e. avoiding mineralisation by selectively ceasing cultivation to prevent further loss of organic soil).

Sub-severe thresholds value for negative synergy

It is proposed that a combination of the sub-severe limitations for *Excess soil moisture* and *Unfavourable texture and stoniness (organic soil)* results in a severe overall rating.

- The *Excess soil moisture* threshold values can be been relaxed to a field capacity duration of 210 days or more.

- The sub-severe threshold can be defined as *organic soil* with organic matter (≥ 30%) of 30 cm or more, either extending down from the surface or taken cumulatively within the upper 100 cm of the soil.

Likely conditions where it can occur

The combination of excess soil moisture and organic soil is widespread in northern and western Europe (Montanarella et al., 2006), in part because wet conditions are essential to the sustenance of the organic material.

3.1.12 Excess soil moisture × Shallow rooting depth

Agronomic rationale for the limitation

Excess soil moisture adversely affects crop growth by restricting rooting conditions and/or reducing soil strength for workability and trafficability (Thomasson and Jones, 1989; Earl, 1997). Temporal patterns in soil moisture conditions are influential drivers for land management. When soils are very wet, nutrient uptake reduces or even ceases altogether (Keane, 2001). Soils are also prone to surface and subsoil compaction if trafficked or cultivated under wet conditions (Herbin et al., 2011), damaging soil structure which can reduce agricultural productivity significantly in subsequent years.

Rooting depth is the maximum depth from the soil surface to where most of the plant roots can extend during a growing season. FAO's "Soil quality for crop production guidelines, SQ3 Rooting conditions"[b] include effective soil depth and effective soil volume related to presence of gravel and stones. The following factors are considered in the evaluation:

- Adequacy of foothold, i.e. sufficient soil depth for anchoring the crop;
- Available soil volume and penetrability of the soil for roots to extract nutrients;
- Space for root and tuber crops for expansion in the soil and economic yield;
- Absence of shrinking and swelling properties affecting root and tuber crops.

The concept of rooting depth being shallow is an important criterion in land evaluation (FAO, 1983). Soils with shallow rooting depth ≤ 35 cm belong mainly to the Leptosols of WRB, and in some cases the Regosols (FAO, 2006; IUSS Working Group WRB, 2006).

Scientific rationale for the limitation

Excess soil moisture combined with *Shallow rooting depth* is likely to have a negative effect on agricultural activity, because the small volume of soil (<2 mm esd) available to plant roots will remain wetter for longer than in deeper soils. The increase in the depth threshold from 30 to 35 cm will not significantly decrease the duration of excess soil moisture in shallow soils.

The shallow rooting depths (30 and 35 cm) are constraints per se on agriculture (Klingebiel and Montgomery, 1966; Bibby and Machney, 1969) and because 35 cm is still a very shallow rooting depth, it will contribute further to the negative interaction.

Sub-severe thresholds value for negative synergy

It is proposed that a combination of the sub-severe limitations for *Excess soil moisture* and *Shallow rooting depth* result in a severe overall rating.

- The *Excess soil moisture* threshold has been relaxed to a field capacity duration of 210 days or more.
- The threshold for *Shallow rooting depth* is relaxed to ≤ 35 cm.

Likely conditions where it can occur

Land with shallow soils experiencing excess soil moisture, is likely to be found in the wetter hill areas bordering the lowlands of central, northern and north-western Europe.

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[b] http://www.fao.org/nr/land/soils/harmonised-world-soil-database/soil-quality-for-crop-production/en/

3.1.13 Unfavourable texture and stoniness (stoniness) × Unfavourable texture and stoniness (sand, loamy sand)

Agronomic rationale for the limitation

Sandy soils have unfavourable hydraulic properties that lead to low water supply (Hall et al., 1977). High contents of coarse fragments in the topsoil exacerbate the water supply problem. Furthermore, the coarse material will contribute to the wear of tillage implements. On the other hand, the water supply problem caused by high amount of coarse material in the topsoil is exacerbated by the sandy texture in the soil profile. Having high amount of coarse material in the topsoil is more limiting to crop growth in case of sandy soils than in finer-textured soils.

Scientific rationale for the limitation

Sandy soils store water accessible to plants at low suctions such that it is easily exhausted (Hall et al., 1977). Furthermore sandy soils have small water holding capacities (Hall et al., 1977) and, combined with high proportion of coarse fragments, water holding capacities will be reduced even more. This is because plant roots rarely penetrate or are unable to penetrate most hard stones and boulders (> 2 mm esd) (Baetens, 2006). This will constitute significant negative synergy.

The interaction between climate and soil properties has been intensively studied by means of mechanistic soil water balance models based on the Richard’s equation. These models and studies (e.g. Belmans et al., 1983) reveal that precipitation deficit leads to more pronounced crop transpiration shortfall in soils with low available water capacity and high hydraulic conductivity. Sandy soils with stony topsoil are characterized by extremely low available water capacity and extremely high hydraulic conductivity, leading to larger transpiration deficiency than in finer textured soils under comparable meteorological conditions.

Sub-severe thresholds value for negative synergy

It is accepted to lower the volume of the coarse material fraction from 15% to 10% w/w, to take into account of the negative synergy, and to lower the cumulative thickness of sandy or sandy loam layers within the upper 100 cm of the soil profile from 50 cm to 40 cm. Both sub-severe thresholds are in line with the maximum 20% margin.

- The sub-severe threshold for *Unfavourable texture and stoniness (stoniness)* is suggested as: volume of coarse fragments of any kind in topsoil is more than 10% including, rock outcrop, boulders.
- The sub-severe threshold for *Unfavourable texture and stoniness (sand, loamy sand)* is suggested as: texture class (fine earth particle < 2 mm esd) in 40% or more (cumulatively) of the 100 cm soil surface is sand, loamy sand (defined as Silt% + (2 x clay%) ≤ 30%).

Likely conditions where it can occur

River valleys in Europe, where fluvial and fluvio-glacial processes have deposited expanses of sands and gravels, are the most likely occurrences for this combination.

3.1.14 Unfavourable texture and stoniness (stoniness) × Shallow rooting depth

Agronomic rationale for the limitation

Unfavourable texture and stoniness (stoniness), with the exception of soft chalk and limestone, will have a negative interaction with *Shallow rooting depth* by further reducing the effective rooting depth for plants as well as the volume of soil for holding water (Hall et al., 1977) and supplying nutrients (Keane, 2001). Thus the volume of stones (> 2 mm esd) and subsequent reduction in volume of fine earth (< 2 mm esd) reduces the capacity of the soil to store water and supply nutrients.

Furthermore, large amounts of coarse fragments in the topsoil can damage/wear cultivation machinery. The size, shape and lithology are important characteristics but these properties cannot be taken into consideration for identifying ANC land. Hard stones, for example quartzite and most igneous rocks, cause excessive wear to farm machinery, and impact significantly negatively on soils that already have shallow rooting depth.

Shallow rooting depth is the maximum depth from the soil surface to where most of the plant roots can extend during a growing season. FAO's "Soil quality for crop production guidelines, SQ3 Rooting conditions"[c] include effective soil depth and effective soil volume related to the presence of gravel and stoniness. The following factors are considered in the evaluation:

- Adequacy of foothold, i.e. sufficient soil depth for anchoring the crop;
- Available soil volume and penetrability of the soil for roots to extract nutrients;
- Space for root and tuber crops for expansion in the soil and economic yield;
- Absence of shrinking and swelling properties affecting root and tuber crops.

The concept of rooting depth being shallow is an important criterion in land evaluation (FAO, 1983). Soils with shallow rooting depth ≤ 30 cm belong mainly to the Leptosols of WRB, and in some cases the Regosols (FAO, 2006; IUSS Working Group WRB, 2006).

Scientific rationale for the limitation

The negative impact of *Unfavourable texture and stoniness (Stoniness)* (with the exception of soft chalk and limestone) is because most other soil materials contain some water and nutrients available to plant root systems but not coarse material (stones, gravel, boulders, etc.). Furthermore, plant roots rarely penetrate or are unable to penetrate most hard stones and boulders (>2 mm esd) (Baetens, 2006). The only benefit of unfavourable stoniness is a positive effect on soil drainage (Sauer and Logsdon, 2002), by increasing porosity of the fine material, but in shallow soils this is not likely to be significant. A further negative effect of this combination is the reduction in the effective volume of soil to sustain plant growth.

Sub-severe thresholds value for negative synergy

It is accepted to lower the volume of the coarse material fraction and to increase the rooting depth to take into account the negative synergy.

- The sub-severe threshold for *stoniness* is suggested as: volume of coarse fragments of any kind in topsoil is more than 10% (w/w) including, rock outcrop, boulders.
- The sub-severe threshold for *Shallow rooting depth* is suggested as ≤ 35 cm.

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[c] http://www.fao.org/nr/land/soils/harmonised-world-soil-database/soil-quality-for-crop-production/en/

Likely conditions where it can occur

The combination of *Stoniness* and *Shallow rooting depth* is likely to be found in hill areas throughout Europe.

3.1.15 Unfavourable texture and stoniness (stoniness) × Steep slope

Agronomic rationale for the limitation

For the criteria *Unfavourable texture and stoniness (stoniness)* and *Steep slope*, indicators and thresholds have been selected to reflect the requirements for water, oxygen and physical stability and possibilities for mechanization of an average crop in Europe. Both coarse soil material and steep slopes affect negatively the possibilities for mechanization. But there seems to be no reason to claim that mechanization in condition of both steep slope and presence of stoniness at a lower level is even more aggravated. However, stoniness (presence of high proportion of coarse material) is associated with low available water capacity in the topsoil and unfavourable conditions for establishment of the crop while steep slope promotes external drainage. Together they may lead to increased soil water deficit.

Scientific rationale for the limitation

According to Rossiter and Van Orshoven (2009), slope does interact with soil moisture balance (not accounted for in the current set of ANC-criteria) and soil moisture balance is affected by texture and stoniness. The result is that steep slopes will typically enhance external drainage and hence may further reduce the water availability in soils with coarse topsoil or sandy profile (Jiang and Thelen, 2004).

Sub-severe thresholds value for negative synergy

It is accepted to lower the fraction of coarse material from 15% to 10% to take into account the negative synergy and to decrease the slope to 12%.

- The sub-severe threshold for *Unfavourable texture and stoniness (stoniness)* is suggested as: volume of coarse fragments of any kind in topsoil is more than 10% including, rock outcrop, boulders.
- For *Steep slope*: a slope gradient larger or equal to 12% may cause limitations when combined with stony soil.

3.1.16 Unfavourable texture and stoniness (sand, loamy sand) × Shallow rooting depth

Agronomic rationale for the limitation

Sandy soils are usually characterized by low fertility, poor structure and low water holding capacity. Indeed, the high hydraulic conductivity due to the sandy texture causes high risk of intense water percolation and nutrient leaching (Pathan et al., 2003), that becomes even more harmful in case of shallow rooting depth (Ichii et al., 2007) since the volume of the water storage in soil is limited.

Also, in some cases, shallow and sandy soils are threatened by surface crust formation and soil erosion (Quinton and Catt, 2004; Benbi and Senapati, 2010). Moreover, this kind of soil is characterized by poor strength for roots anchorage, hence exposing crops to risk of lodging (Sterling et al., 2003; Mooney et al., 2007) in windy and hilly areas.

Scientific rationale for the limitation

Sandy soils are usually characterized by poor structural stability mainly due to low organic matter content (the primary binding agent in aggregates formation), and to the lack of cohesion among soil particles because of the unfavourable area to volume ratio (Bronick and Lal, 2005), since area and volume increases with the square and the cube of the diameter, respectively. This poor soil structure has several negative implications – such as the high sensitivity to surface crusting, wind erosion, water percolation and nutrient leaching, and the often low buffer capacity that could severely restrict the agricultural land use of this class of soils (Abu-Awwad and Shatanawi, 1997; Franzbluebbers, 2002). In case of a shallow sandy soil, these negative implications may even become more severe, especially for the interaction between reductions in water holding capacity and rooting depth (Fernandez-Illescas et al., 2001). Indeed, such sandy soils hold less water than silty or loamy soils of the same depth, not allowing enough moisture recharge before the start of the growing season (Ceballos et al., 2002).

Moreover, since water losses through percolation, evaporation and subsurface runoff are very fast in thin and coarse sandy soils (Ceballos et al., 2002), water is available for plants just for a short time, leading to increased inter- and intra-specific competitions (Semenov et al., 2009). In dry areas, erosion of nutrients and shortage of available water could constrain plant growth and development (Valentin and Bresson, 1992; Dekker and Ritsema, 1994). As known, deep soils may sometimes ensure satisfying production levels even in environments characterized by small capacity to holed water (Dreccer et al., 2002; Comas et al., 2013), whereas shallow soils under the same hydraulic conditions can expose plants to severe mid- or late-season water stress (Manshadi et al., 2006).

Sub-severe thresholds value for negative synergy

The negative interaction described justifies relaxing the sub-severe thresholds. In a sandy or loamy sand soil a lower proportion of sand in the topsoil and a higher water holding capacity through increased rooting depth would be necessary in order to better meet crop water requirements.

- The sub-severe threshold for *Unfavourable texture and stoniness (sand, loamy sand)* is suggested as: texture class (fine earth particle < 2 mm esd) in 40% or more (cumulatively) of the 100 cm soil surface is sand, loamy sand (defined as Silt% + (2 x clay%) ≤ 30%).

- The sub-severe threshold for *Shallow rooting depth* is ≤ 35 cm.

3.1.17 Unfavourable texture and stoniness (sand, loamy sand) × Poor chemical properties (salinity)

Agronomic rationale for the limitation

In sandy soils, crop growth can be limited due to water stress from the low soil water-holding capacity and adverse weather conditions. Sandy soils have very small nutrient holding or supplying capacity so normal fertilization practices have limited efficiency (Van Orshoven et al., 2014). Additionally sandy soils are highly susceptible to accelerated water and wind erosion (Hudson, 1995) and accordingly require additional soil conservation practices.

Many crop and pasture plants cannot survive under high saline conditions. On saline areas with agricultural production, salinity has three main negative impacts on crops that can cause significant losses of productivity (Van Orshoven et al., 2014):

- With increasing salinity the water extraction from the soil becomes more difficult for crops.
- Soil structure is damaged and plant growth can be limited by the increasing content of toxic substances.
- The damaged soil structure and the reduced vegetation cover increase the risk of soil erosion both by wind and by water.

Scientific rationale for the limitation

Field capacity (the maximum amount of water that can be retained by the soil against gravity) is low in sandy soils. The plant available water capacity is generally smaller than in finer textured soils but particularly small in medium and coarse sands. More importantly, most of the plant available water in sandy soils is held at low suctions and therefore extracted easily by plant roots (Hall et al., 1977), so that water stress develops rapidly when rainfall ceases and a period of drought begins.

Plant growth being a function of total moisture stress, which is the sum of soil moisture tension and the osmotic pressure of the soil solution (Regional Salinity Laboratory, 1954), means that as soil salinity increases plants extract water with increasing difficulty, aggravating water stress conditions.

The second interaction between sandy texture and salinization is that saline groundwater level rises near to soil surface more rapidly in sandy soils than in finer-textured soils (Di Gleria et al., 1962), as the velocity of capillary rise is high in sandy soils. This is one of the natural processes increasing the level of salinization (Regional Salinity Laboratory, 1954).

The third relationship is the effect of salinity on the risk of erosion on sandy soils. They are especially susceptible to wind erosion because of the single grained structure (absence of aggregates) and low clay and normally low humus content (Shao, 2008). As plant growth is reduced by salinity, vegetation cover is sparse, augmenting the risk of erosion (Wolfe and Nickling, 1993).

Sub-severe thresholds value for negative synergy

- Sub-severe threshold for *Unfavourable texture and stoniness (sand, loamy sand)* is: sand, loamy sand texture in at least 40% of 100 cm surface layer for sandy texture and
- Sub-severe threshold for *Salinity* is ≥ 3.2 dS/m in topsoil.

Likely conditions where it can occur

The saline sandy littoral and adjacent marshlands on coasts or in alluvial plains.

3.1.18 Unfavourable texture and stoniness (heavy clay) × Shallow rooting depth

Agronomic rationale for the limitation

Shallow soils may hinder normal tillage (for which the standard depth is 15 to 25 cm). The constraint is serious especially if the shallow depth is due to the presence of rock or hard pan. Normally, shallow clay soils are used for pasture rather than for arable cropping.

Roots grow into the soil to extract soil-bound water and nutrients and in shallow soils water is rapidly exhausted (Van Orshoven et al., 2014).

A clayey texture of the topsoil affects plant nutrient supply, soil moisture conditions, rooting conditions, ease of tillage and movement of stock (especially cattle). The moisture availability depends on the amounts of rain in relation to evapotranspiration, and the permeability of the soil profile. If there is a hardpan or solid rock within rooting depth, the internal drainage will be hampered and surface ponding may occur. As long as the soil is wet it is susceptible to smearing and compaction by traffic of machinery and trampling by stock. In turn, compaction affects the rootability and aeration of the soil, leading to reduced crop yields.

In long dry periods, the clay topsoil of shallow soils will dry out faster and further than clay topsoil of deeper soils, thus shortening the time span for field activities and shortening the effective growth periods.

As a result of typical soil moisture dynamics, shallow soils comprised of heavy clay are sensitive to both drought and wetness. Neither of these conditions are favourable for agriculture, which qualifies the combined limitation as having negative synergy.

Scientific rationale for the limitation

A shallow soil with a heavy clay topsoil can, in most cases, be conceived as a one layer soil above a substratum of rock or hard pan. As a result of the shallow rooting depth, the volume of the soil is smaller hence there is no buffer for water storage and nutrient supply in the subsoil. Under the same rainfall, evaporative demand and plant density, the processes of change (on a per unit soil volume basis) is faster than in deep soils, thus leading to more rapid changes in soil moisture status, and to more frequent occurrence of plant growth stress. When compared to heavy clay topsoil on slightly deeper soils, the shallow rooting depth acts as a strong constraint. Similarly when compared to slightly lighter textured topsoil in shallow soils, the heavier texture acts as a stronger constraint. The two limitations when combined strengthen each other, leading to negative interaction and aggravated constraint level.

Sub-severe thresholds value for negative synergy

Given the negative interaction between shallow rooting depth and a topsoil of heavy clay, relaxing the severe threshold values for both limiting criteria, when occurring in combination, is justified.

- The sub-severe threshold for topsoil *heavy clay* is thus defined as clay content ≥ 50%.
- The sub-severe threshold for *Shallow rooting depth* is increased to ≤ 35 cm.

Likely conditions where it can occur

Shallow soils are widespread in steeply sloping areas, where erosion processes have removed the topsoil. They may overlay hard rocks or densely packed, cemented subsoil. Heavy clays in such areas are often associated with the presence of basic rocks, such as marl, basalt, or limestone (Finke et al., 2001). However, across Europe as a whole, shallow heavy clay soils are much less extensive than shallow coarse textured soils.

3.1.19 Unfavourable texture and stoniness (heavy clay) × Poor chemical properties (salinity)

Agronomic rationale for the limitation

The combination of heavy clay and salinity in the topsoil leads to mutual interaction through the effects of salt and clay on soil moisture and nutrient availability, and on soil structure.

With regard to agriculture, the consequences of soil salinity include:

- Significant losses of productivity with increasing soil salinity because it becomes increasingly difficult for plants to extract water from the soil (aggravation of drought stress for plant roots) (Van Orshoven et al., 2014).
- Damaged soil structure lowers hydraulic conductivity and makes a clay topsoil impermeable. High salinity itself favours structural stability of clay, but wetting of the soil lowers the salt concentration, and favours mud formation.
- Imbalance in nutrient content, making them less available, or even leading to toxicity, that may be limiting to plant growth (Driessen et al., 2001).

Scientific rationale for the limitation

In heavy clay topsoils, the salt may not be visible, as long as the salt crystals are hidden in the structured clay. But under influence of rainfall, the salts may cause a peptization of the clay surface, and the structured clay aggregates may turn into mud, and become a crust when dry. Evaporation of stagnant waters may leave considerable amounts of salts on the soil surface (Brinkman, 1980).

The presence of salt favours development of strong structures in clay soils under dry conditions, but during the moist winters clay soils become wet, muddy, and impermeable (Driessen et al., 2001).

In normal clay soils, plant roots extract water from the soil by pulling harder than the soil matrix suction, or matrix potential (usually measured in kPa). In saline clay soils, the total potential is even higher, because the osmotic potential of the soil water solution is added to the matrix potential.

Localised redistribution of salts can often cause salinity problems of a significant magnitude. Soluble salts move from areas of higher to lower elevations, from relatively wet to dry areas, from irrigated fields to adjacent rainfed fields, etc. Salts may also accumulate in areas with restricted natural drainage caused by development activities (road or railway construction).

Sub-severe thresholds value for negative synergy

The main justification to accept a negative synergy for the criteria combination of heavy clay topsoil and topsoil salinity is the increased drought stress, as the presence of salts makes the extraction of water more difficult for plant roots, whereas in clay soils the water is already hard to extract due to the high matrix suction. The constraint is thus accumulated by the two factors.

Threshold values for the interaction can be set to the maximum allowed for both criteria when occurring in combination. It means areas having topsoil with a salinity between 3.2 and 4.0 dS/m, and a clay content between 50 and 60%.

- The sub-severe threshold for *Unfavourable topsoil texture (heavy clay)* is defined with clay ≥ 50%.
- The sub-severe threshold for *salinity* is ≥ 3.2 dS/m in topsoil.

Likely conditions where it can occur

Concentrations of saline soils occur in the river deltas and coastal and river plains. Heavy clay topsoils occur mainly in river back swamps, and marine and lacustrine plains.

If the capillary rise from shallow groundwater reaches the soil surface, such as in low lying depression areas, then the salt accumulates at the surface (external salinization). Such salt accumulation from the groundwater is typical for arid and semi-arid climates in low-lying land. The salt can also be brought by flooding with sea water or slightly saline river water, or by runoff from surrounding sloping land.

3.1.20 Unfavourable texture and stoniness (heavy clay) × Poor chemical properties (sodicity)

The combination of a heavy clay topsoil and soil sodicity refers to soil profiles with a very high clay content, which is slightly sodic.

The sodicity limitation does not make a distinction between sodic and non-sodic topsoil, both are possible. The heavy clay topsoil may overlay a sodic subsoil layer having an even heavier texture originating from clay illuviation, but the heavy topsoil may also be the upper part of the former subsoil which had become the topsoil, after the original surface was washed away.

Agronomic rationale for the limitation

Heavy clay soils have slow permeability when wet and are susceptible to waterlogging as excess water ponds on the soil surface after even moderate rains rather than drains downwards through the soil profile. Heavy clays are difficult to cultivate and, although the available water capacity is neither large nor small, the water is held at large suctions (high tension) making it difficult for plant roots to extract it.

Heavy clay topsoil limits the available time for farming operations. Conventional tillage is possible only in a narrow moisture range (Van Orshoven et al., 2014). Grazing season is shortened because of the inaccessibility of the land and because of the high risk of compaction during wet conditions.

Sodic soils have two main unfavourable impacts on crop production, both are indirect. Sodicity enhances (i) the risk of waterlogging and (ii) the risk of erosion on sloping land, through the degradation of soil physical properties (Tanji, 1990). Many sodic soils have also a pH above 8, which is above the optimum range for most crops. The high pH is related to the presence of free sodium carbonate.

Clay soils are highly sensitive to sodicity. The coexistence of sodicity and heavy clay topsoil results in an even higher risk of waterlogging that causes reduced crop growth through poor aeration and limits the possibilities and the available time for agricultural operations and for grazing.

Scientific rationale for the limitation

Sodicity refers to the presence of a high proportion of adsorbed sodium in the clay fraction of soils. Sodicity causes a poor aggregate stability when wet, resulting in unstable soils, while when dry the Exchangeable Sodium Percentage (ESP) favours structural stability. The soil behaviour depends also on the proportion of Ca-Mg-Na composition of the cation exchange complex. The sodium-induced soil dispersion causes loss of soil structure, reduced soil permeability and lower infiltration. It leads to lower plant available water, increased runoff and soil erosion. Poor internal drainage leads to a waterlogged soil, and anaerobic conditions that reduce or even prevent crop growth. When sodium-rich groundwater is present, the sodium will be absorbed by the clay particles leading to increased ESP. The sensitivity for erosion can result in muddy river water downstream, and sedimentation.

Sub-severe thresholds value for negative synergy

The negative synergy of sodicity and clay soil properties is because they both lead to waterlogging and poor aeration. Therefore sodic soil combined with high clay content in the topsoil can result in a constraint to agriculture.

- The sub-severe threshold for *Unfavourable topsoil texture (heavy clay)* is defined with clay ≥ 50%.
- The sub-severe threshold for *sodicity* is ≥ 4.8 ESP in half or more (cumulatively) of the 100 cm soil surface layer.

Likely conditions where it can occur

Solonetz (strongly sodic soils) and their weakly sodic intergrades occur predominantly in areas with a steppe climate (dry summers and an annual precipitation in the range 400-500 mm), in particular in flat lands with impeded vertical and lateral drainage. Smaller occurrences are found on inherently saline parent materials (e.g. marine clays or saline alluvial deposits) (IUSS Working Group WRB, 2006). Occasionally, sodicity occurs also in higher-rainfall areas, e.g. in depressions without outlet.

3.1.21 Unfavourable texture and stoniness (heavy clay) × Poor chemical properties (acidity)

Agronomic rationale for the limitation

Soil acidity affects nutrient availability and overall soil conditions for plant growth. Low soil pH increases aluminium availability and therefore toxicity for plants, while limiting availability of most nutrients (Van Orshoven et al., 2014).

All these properties and processes have negative effects on farm management (higher costs, greater yield losses), and are added to the already existing limitations of heavy clay topsoil, which are low structural stability, low permeability, poor workability and difficult conditions for root growth.

In terms of management, soil pH measurement helps to predict the requirement, the transformation and the effectiveness of fertilizers, amendments and reclamation materials. Soil acidity problems are conventionally solved by the addition of liming materials and reclamation materials.

Scientific rationale for the limitation

Clay soils in the European temperate and Mediterranean climates have usually a neutral or basic soil reaction. In some very special cases, especially under moist, well drained and warm conditions, a long process of leaching of basic cations such as Ca^{2+}, Mg^{2+}, and K^{+} may have led to clayey soil with a relatively low base saturation and low pH. The resulting weathered soil profile may consist of a high proportion of Fe and Al oxides which are acid and low in nutrients. The acidity of a heavy clay soil can also be the result of the formation of acid sulphate soils (Thionic Fluvisols and thionic subgroups in the WRB). An acid clay soil is extremely contrasting with vertic and sodic soils, which have high pH and are rich in bases and nutrients.

Application of fertilizer may also contribute to soil acidity, notably applications of NH_4^+ producing fertilizers (e.g. urea, anhydrous NH_3), through oxidation of NH_4^+ to NO_3^- and H^+.

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, 2007). Lower (acid) pH values indicate soil conditions that may limit crop yield.

Sub-severe thresholds value for negative synergy

The combination of heavy clay texture and acidity in the topsoil leads to a strengthening of the overall severity of the constraint. The reason is mainly the lower nutrient availability, combined with toxicities and deficiencies, which are added to the existing limitations of heavy clay.

A relaxation of thresholds for the combination of heavy topsoil and soil acidity is reasonable, allowing the maximum clay content at 50% and the pH threshold at 5.5.

- The sub-severe threshold for *Unfavourable topsoil texture (heavy clay)* is defined with clay ≥ 50%.
- The sub-severe threshold for soil *acidity* in the topsoil is defined with pH ≤ 5.5 (measured in water).

Likely conditions where it can occur

The combination of heavy clay topsoil and low pH is atypical for Europe. It may be found in glacial landscapes where dense heavy clay layers have been formed under the ice, in original coastal and lacustrine sediments, e.g. acid-sulphate soils.

A closely related reference soil group from WRB is the Alisol, of which minor occurrences have been reported around the Mediterranean Sea and also in humid temperate regions (IUSS Working Group WRB, 2006).

3.1.22 Shallow rooting depth × Poor chemical properties (salinity)

Agronomic rationale for the limitation

Shallow soils can markedly limit crop productivity because of the reduction in the volume of soil where crops can extract water and nutrients. In addition, the simultaneous occurrence of salinity in the rhizosphere can severely affect both economic and environmental sustainability of agriculture, although the overall result largely depends on (i) rainfall amount and distribution, (ii) fertility of the substrate, (iii) drainage capacity of such dense and shallow soils. Moreover, the constraints to deep percolation due to shallow rocks or hard pans prevent the leaching of salts beyond the rooted zone, greatly limiting the possibility of successful soil remediation.

Scientific rationale for the limitation

Salinity reduces the capacity of the soil to supply plants with water. Indeed, high loads of salts in the rooted zone decrease the osmotic potential of the soil solution, which in turn lower the soil water potential. As result, the force that holds water in the soil becomes greater, thus reducing the amount of water available for plants (Ayers and Westcot, 1994; Hasegawa et al., 2000; Munns, 2002; Castillo et al., 2007). This phenomenon is amplified as the volume of water held in the soil is limited by shallow rooting depth.

Moreover, saline soils are prone to cracking and fissuring which may lead to fast water loss from the rhizosphere (Miller and Donahue, 1995), in turn further reducing the already low plant available water in shallow soils. Salinity has also a negative impact on plant's nutritional status (Taiz and Zeiger, 2006), since it (i) decreases the osmotic potential in the soil solution thus limiting the uptake of nutrients, and (ii) leads to a competition effect that reduces the selective absorption of K^+, Ca_2^+ and NO_3^- when toxic ions (Cl^- and Na^+) are present in the soil solution.

Sub-severe thresholds value for negative synergy

The negative interaction of this combination justifies lowering the salt concentration and increasing rooting depth for the sub-severe thresholds to allow for a higher water holding capacity, a higher nutrient uptake and less costly remediation measures.

- The sub-severe threshold for *Shallow rooting depth* is ≤ 35 cm.
- The sub-severe threshold for *salinity* is ≥ 3.2 dS/m in topsoil.

3.1.23 Shallow rooting depth × Poor chemical properties (sodicity)

Agronomic rationale for the limitation

Sodicity is a serious limiting factor for agriculture especially when it occurs in shallow soils, where the effective rooting depth and the amount of water that a plant can extract from the soil are severely constrained (Irvine and Doughton, 2001). Under these conditions, sodicity could lead (i) to the development of surface crusts that severely reduce water infiltration during the dry season and (ii) to the formation of dense structures in the subsoil during the wet season, reducing water drainage and leading to soil saturation for long periods. These conditions strongly restrict crop growth while reducing – at the same time – the available working time and the feasibility of agricultural operations, such as tillage and planting. The lack of salts leaching towards deeper soil layers increases the sodium concentration in the rooted soil layer, which becomes very hard to manage and remediate (De Sutter, 2008).

Scientific rationale for the limitation

Sodicity could hamper the agricultural land-use of shallow soils (Irvine and Doughton, 2001; Ferguson et al., 2006) by making the thin layer explored by roots even more unsuitable. The direct constraint results from stress and/or toxic effects on plant and roots due to the high sodium concentration in the topsoil (Bernstein, 1975; Dodd, 2007). The indirect constraint comes from physical limitations due to high soil strength and poor aeration (Dodd, 2007) or from the decrease in available water and nutrients because of the increase in the osmotic potential induced by the sodium cation in the soil solution (Zhang et al., 2002).

A high sodium concentration in the soil is responsible, at the plasma membrane level, for the lowered plant ability of fixing calcium (Yermiyahu et al., 1994) and for the decreased selectivity for potassium uptake (Cramer et al., 1987). This leads plants to produce shorter and thicker roots characterized by a low density of hairs compared to those grown in standard media.

The formation of a dense and impermeable soil matrix hinders the deepening of roots on the one hand because of anoxic conditions in the topsoil, on the other hand by promoting the expansion of root cells radially rather than axially (Dodd, 2007). Moreover, the presence of sodium as exchangeable cation results in the alteration of the soil redox potential and pH, reducing the availability of micronutrients and nitrogen for plants. Indeed, the poor aeration conditions that could occur in sodic soils promote denitrification and markedly limit mineralization, thus reducing the available nitrate, which is also inhibited via precipitation by chloride or sulphate ions, which are usually abundant in this kind of soils (Levy and Shainberg, 2005).

Sub-severe thresholds value for negative synergy

According to the above described negative interaction:

- The sub-severe threshold for *Shallow rooting depth* is ≤ 35 cm.
- The sub-severe threshold for *sodicity* is ≥ 4.8 ESP in half or more (cumulatively) of the 100 cm soil surface layer.

3.1.24 Shallow rooting depth × Steep slope

Agronomic rationale for the limitation

Shallow soils are sub-productive since they cannot provide sufficient stability, water and nutrients to growing crops or to buffer against toxic substances.

All other factors being equal, steep slopes are a handicap for agriculture since they make mechanisation of the field and crop management operations difficult and give rise to increased soil erosion.

On steep slopes the mechanised tillage or root crop harvesting on shallow soil will be even more delicate in terms of risk of damage to equipment, so that a negative synergy is likely. Since in shallow soils crop root development may be weaker and soil loss by water and wind erosion may be increased on steep slopes compared with less steep slopes. Moreover, steep slopes increase external soil drainage so that rapid exhaustion of the soil water available at the beginning of the growing season may occur.

Scientific rationale for the limitation

In shallow soils the amount of water that can be stored is limited (Jiang and Thelen, 2004). This aspect of the negative synergy will be more pronounced under a dry climate.

Ploughing and root crop harvesting on shallow soils requires fine-tuned equipment and considerable farmer experience. If in addition these operations must be performed on steep slopes, limitations and risks for equipment damage increase.

Erosion of shallow soil on steep slope will more quickly lead to productivity losses than in case the soil is less shallow or the slope less steep (Clarke and Rendell, 2000).

Sub-severe thresholds value for negative synergy

To take into account the negative synergy it is justified to increase rooting depth from 30 cm to 35 cm and to decrease the slope to 12% for the sub-severe threshold.

- The sub-severe threshold for *Shallow rooting depth* is ≤ 35 cm.
- For *Steep slope* the gradient is ≥ 12% when combined with shallow rooting depth.

Likely conditions where it can occur

Land with shallow soils on steep slopes is likely to be found in the wetter hill areas bordering the lowlands of central, northern and north-western Europe, but sporadically in southern Europe as well.

3.1.25 Poor chemical properties (salinity) × Poor chemical properties (sodicity)

Agronomic rationale for the limitation

Many crop and pasture plants cannot survive under high saline conditions. On saline areas with agricultural production, salinity has three main negative impacts on crops that can cause significant losses of productivity (Van Orshoven et al., 2014). Main reasons are: (i) with increasing salinity, the water extraction from the soil becomes more difficult for crops; (2) soil structure is damaged and plant growth can be limited by the increasing content of toxic substances; (3) the damaged soil structure and the reduced vegetation cover increase the risk of soil erosion by both wind and water.

Sodic soils have two main unfavourable impacts on crop production, both are indirect. Sodicity enhances the risk of waterlogging and the risk of erosion through the degradation of soil physical properties (Tanji, 1990). Further difficulty is that the sodium is not leachable with just water, but must be replaced by soluble calcium (Wildman, 1981). Additional negative impacts of sodic soils include less available water for plants, poor tilth and sometimes a black crust on the surface formed from dispersed organic matter (McCauley and Jones, 2005). Ivits et al. (2013) found that productivity of European sodic soils is lower than that of saline soils.

Co-existence of salinity and sodicity soil properties leads to unfavourable soil water conditions affecting the growth and yield of most crops. Saline sodic soils are almost impermeable to infiltrating water (Qadir et al., 1998). Management of salinity and sodicity becomes more complicated when both conditions occur together (NDSU Extension Service). Conventional reclamation procedures using gypsum amendment, followed by vertical leaching, lead to poor economical returns from these soils (Qadir et al., 1998).

Scientific rationale for the limitation

Soil sodicity is frequently associated with soil salinity because Na^+ is preferentially adsorbed over Ca^{2+} and Mg^{2+} as salinity increases and because of the selective precipitation of calcium minerals as the soil solution is evapo-concentrated (Bresler et al., 1982). The ratio of salinity (EC) to sodicity (ESP) is the driving factor determining the effects of salts and sodium on soils.

The combination of salinity and sodicity (saline-sodic soils) means that the water soluble salt concentration, the quality and the distribution of salts are similar to those of saline soils. A massive layer with columnar structure, which is characteristic for sodic soils (sodic subsoil), is also present. This layer with columnar structure is usually located near the soil surface and at the same time it is the layer of the highest salt accumulation. The water management of these soils is extremely unfavourable due to the very low water permeability caused by both the water soluble Na-salts and the exchangeable sodium content. The soil surface as well as the sodic subsoil become extremely plastic when wet.

Though salinity can off-set in some degree the effects of sodicity causing flocculation (Shainberg and Letey, 1984), it has a more dominant negative and potentially lethal effect on plants due to the osmotic potential and toxicity (Bresler et al., 1982).

The increase of salt content reduces soil productivity (Szabolcs, 1974) hence sodic soils with a higher salt content (salinity) in addition are even less productive. Moreover in saline-sodic soils the alkaline hydrolysis has further negative impacts such as toxicity, and an indirect negative effect on soil structure (Suarez et al., 1984).

The natural vegetation is very poor which is also proof for the very low productivity of saline-sodic soils (salt-sodium tolerant species, e.g. plant community *Crypsido aculeatae–Suaedetum maritimae*; Borhidi, 2007) with high extent of bare soil (e.g. Cisneros et al., 1999; Wang et al., 2013).

Sub-severe thresholds value for negative synergy

According to the above described negative interaction, the coexistence of salinity and sodicity at a sub-severe threshold is limiting for agriculture. Threshold values for the interaction can be set to the maximum allowed for both criteria when occurring in combination.

- The sub-severe threshold for *salinity* is ≥ 3.2 dS/m in topsoil.
- The sub-severe threshold for *sodicity* is ≥ 4.8 ESP in half or more (cumulatively) of the 100 cm soil surface layer.

Likely conditions where it can occur

Plains with shallow water table, saline groundwater and negative water balance where highly saline soils become sodic naturally.

3.2 Positive synergies

A positive synergy occurs when two criteria, which individually present a sub-severe limitation to agriculture, compensate each other removing any overall severe constraint.

3.2.1 Excess soil moisture × Steep slope

Rationale for removing the limitation

Excess soil moisture (Jones and Thomasson 1985) results from inadequate soil drainage, a high water table, seepage or runoff from surrounding areas, which adversely affect crop growth by restricting rooting conditions (Cannell et al., 1985) and reducing soil strength for workability and trafficability (Earl, 1997; Thomasson and Jones, 1989).

Soils are also prone to soil compaction if trafficked or cultivated under wet conditions (Herbin et al., 2011), damaging soil structure, which can reduce agricultural productivity significantly in subsequent years.

Steep slopes (Bibby and Mackney, 1969) are often associated with shallower soils, e.g. Leptosols, Regosols of WRB (IUSS Working Group WRB, 2006), with less capacity to retain water due to gravity. Therefore steep slopes should have a positive effect reducing excess soil moisture and consequently on improving agricultural activity. Such conditions would reduce the duration of field capacity, in addition to the rapid runoff of surplus water from steeply sloping land.

3.2.2 Unfavourable texture and stoniness (stoniness) × Unfavourable texture and stoniness (organic soil)

Rationale for removing the limitation

Organic soils have low bulk density, limited physical stability and weak soil strength resulting in poor trafficability (Pietola et al., 2005). The bearing capacity of the soils is very small, especially during wet periods when organic soils are much more at risk of suffering severe structural damage by traffic (animals as well as machinery) than most mineral soils. However, the presence of gravel and stones, alone or mixed in the finer textured mineral compounds, should increase the soil strength and thus trafficability sufficiently that access for grazing animals is improved by the combination.

Apart from reducing the volume of soil able to hold water and supply nutrients especially in areas with pronounced dryness, large amounts of coarse material > 2 mm (Hodgson, 1978) in the topsoil can damage/wear cultivation machinery. References to historic land use may shed some light on the use possibilities and limitations, e.g. the history of potato growing in Ireland on boggy soils on stony hill slopes (Vullings et al., 2013).

In the lowland peat regions of the Netherlands farmers have tried to improve accessibility of the land by collecting debris (sand and bricks from cities) and for spreading it on the land surface during past centuries. This demonstrates that coarse mineral material alleviates the constraint of low bearing capacity in organic soils.

Consequently, stones or gravel in the topsoil of organic soils are likely to improve soil strength and trafficability, improving accordingly access for animals. Indeed, the dominant agricultural land use for organic soil with stony topsoil is grazing.

3.2.3 Unfavourable texture and stoniness (sand, loamy sand) × Unfavourable texture and stoniness (organic soil)

Rationale for removing the limitation

Experiments with peat stabilized with sand columns show that measured soil strength and compressibility of the peat-sand mixtures are improved (Jorat et al., 2013) when sand is added to peat soil. Therefore it is suggested that a mixture of sandy material and organic matter is beneficial for agriculture, especially for high value horticultural crops. The sand stabilises the peat and, as Jorat et al. (2013) have demonstrated, higher shear strength and permeability was achieved. Within the definition of these materials, the soil is classified as Sandy Peat (Hodgson, 1997).

Combination of soil characteristics such as sand content of 40% or more and rich organic content may have a positive impact on agriculture by increasing the hydraulic conductivity and thus the aeration of the soil profile allowing water to percolate down into the substrate or drain laterally below the surface. Hall et al. (1977) have shown that the volume of coarse pores (> 60 µm) in sandy soils is significantly larger (25% v/v) than in heavier textured soils (8-15% v/v), which is a benefit for most agricultural activities. However, because water can percolate rapidly through sandy soils, the nutrients they contain can be easily washed out.

In general, organic soil material has even a larger volume (25-30% v/v) of coarse pores (> 60 µm) and much lower bulk density (Hall et al., 1977) than sandy materials and consequently internal drainage is rapid when water tables are low. However, the bulk density of peat soils (0.2-0.8 t m^{-3}; Hammond and Brennan, 2003) is much less than the bulk density of sandy soils (1.3 - 1.6 t m^{-3}; Hall et al., 1977). Consequently, the bearing strength of organic soils is much less than that of sandy soils.

Sandy peat has a higher bulk density 0.7 to 0.96 t m^{-3} and therefore greater bearing strength than pure organic soil material (peat), which would be beneficial for agriculture. Depending on the nature of the mineral particles, the sandy peat may be a more fertile medium for plant growth.

Likely conditions where it can occur

This criteria combination occurs mainly on the margins of peatland where the organic material is mixed with mineral soil material.

3.3 Unclear synergies

An unclear synergy occurs when both positive and negative synergies are detected, and/or when the outcome of the combination depends on external factors which are not known or which can act differently according to the specific situation.

3.3.1 Excess soil moisture × Unfavourable texture and stoniness (stoniness)

Agronomic rationale for the unclear synergy

Excess soil moisture (Jones and Thomasson, 1985) adversely affects crop growth by restricting rooting conditions (Cannell et al., 1985) and reducing soil strength for workability and trafficability (Earl, 1997; Thomasson and Jones, 1989). These effects are exacerbated in areas of high rainfall (>1000 mm annually). Temporal patterns in soil moisture conditions are influential drivers for land management.

Soils are also prone to soil compaction if trafficked or cultivated under wet conditions (Herbin et al., 2011), damaging soil structure, which can reduce agricultural productivity significantly in subsequent years. For example, Jones (1975) compared surface bearing strengths for soils of different texture and structure, in relation to the hoof pressure exerted by grazing animals. Soil moisture contents at 5 kPa resulted in surface bearing strengths for all textures and structures that were too low to support beef or dairy cattle.

Presence of coarse fragments (> 2 mm) (with the exception of soft chalk and limestone), reduces the volume of soil able to hold water and supply nutrients and is thus detrimental to crop growth. Furthermore, large amounts of coarse fragments in the topsoil can damage/wear cultivation machinery, which is generally regarded as unfavourable for agriculture (Klingebiel and Montgomery, 1961; MAFF, 1988).

Scientific rationale for the unclear synergy

Presence of stones should improve internal soil drainage in land experiencing excessive soil moisture, by improving overall porosity, through increasing the aeration in the soil (Hall et al., 1977). However, the volumetric reduction in the capacity of the soil to store water and supply nutrients, and the wear to farm machinery are outweighed by the important potential of coarse fragments (> 2 mm) to reduce the duration of excessive soil moisture.

Therefore the combination of *Excess soil moisture* and *Stoniness* is likely to have both positive and negative impacts on agricultural activity, but it is uncertain which impact prevails.

The negative impact of stoniness is because of the wear to agricultural machinery (MAFF, 1988). There is likely to be a positive effect as well because stones can improve the drainage status of soils, by increasing porosity of the fine material (< 2 mm). However, most stones reduce the effective volume of the soil that can supply nutrients. Again with the exception of soft chalk and limestone, which can have a plant available water capacity of 20% or more (Gras and Monnier, 1963), hard stones such as quartzite or basalt contain no water available to plants. Hence the impact on crop growth during dry spells depends in part on the stone lithology, but on land with excessive soil moisture combined with unfavourable stoniness, this is unlikely to be a significant issue.

Likely conditions where it can occur

Stoniness in combination with *Excess soil moisture* at sub-severe level is most likely to occur in northern and western Europe.

3.3.2 Unfavourable texture and stoniness (organic soil) × Steep slope

Agronomic rationale for the unclear synergy

For agricultural use, the steepness, regularity, shape, orientation and length of the slope are relevant for farm operations, water management and erosion risk. A steep slope makes land management difficult, especially when working with large machines, and increases the runoff. Organic soils often suffer from excessive wetness and low soil strength.

The combination of *Steep slope* and o*rganic soil* impacts negatively on mechanized farming because of slope limitations (Klingebiel and Montgomery, 1966) and weak soil strength. However, better external drainage because of increased runoff on steep slopes and warmer temperatures on south facing slopes would impact positively on the use of the land, leading to an unclear synergy.

Likely conditions where it can occur

Fields with organic soil on sloping areas occur mainly under cold and humid climates on hilly and mountainous land in northern Europe.

3.3.3 Unfavourable texture and stoniness (stoniness) × Unfavourable texture and stoniness (heavy clay)

Agronomic rationale for the unclear synergy

Trafficability, workability and rootability are the key qualities determining the agricultural potential of land combining a heavy clay texture and coarse fragments in the topsoil. Also its sensitivity to physical soil degradation has to be considered. All these qualities together have an influence on hydrological conditions, and the resulting soil moisture and nutrients availability.

Scientific rational for the unclear synergy

In general, some land qualities associated with heavy clay topsoil are negatively influenced by stoniness: excessive wear of tillage equipment, or prevention of tillage. Coarse fragments directly reduce the volume of soil exploitable by roots, thus reducing water-holding capacity and nutrient supply.

On the other hand, a few land qualities may be positively influenced: coarse fragments can help aerate the soil and provide paths for rapid water entry especially for heavy textured soils, better water infiltration and percolation, so that there is less runoff and shortening of too wet periods (Van Orshoven et al., 2014). Also the coarse fragments may speed up the warming up of the soil in spring.

In the special case of a thin gravel layer on the soil surface, the layer acts as a mulch layer, protecting the soil profile from excessive heating and lowering the evaporation, and thereby conserving soil water, and providing protection to drying out (Kaseke et al., 2012).

Consequently, given the occurrence of both positive and negative properties, it is thought to have an unclear synergy as the outcome of the combination may also result from the specific characteristics of the coarse material.

Likely conditions where it can occur

Stony heavy clay topsoil is likely to occur in landscapes of colluvial origin, especially in hilly and mountainous regions having basic rock types from which the weathering leads to the formation of clays. It may also occur on in-situ weathered clays, or on clays in floodplains, on which gravel has been deposited under alluvial/colluvial conditions.

The coarse material (of any kind: gravel, stones, boulders and rock) can be found alongside a topsoil of heavy clay in various ways, depending on the landscape formation. In colluvial soil profiles, the coarse material may have been mixed with the fine material, and then it occurs from the soil surface downwards, mixed with the clay soil. On eroded slopes a relatively thin clay soil may overlay a coarse substratum. In alluvial sites gravelly soil layers can be found just below, or intermingled with clay sediments. A very special situation may be distinguished when a heavy clay topsoil is covered by a layer of coarse material on the surface, e.g. a desert pavement (Kaseke et al., 2012).

This combination is more likely to occur under pasture than under cropping.

3.3.4 Unfavourable texture and stoniness (sand, loamy sand) × Unfavourable texture and stoniness (heavy clay)

Agronomic rationale for the unclear synergy

The combination of a heavy clay topsoil and the occurrence of sand or loamy sand within 1 m of the soil surface layer is possible but leads to a very contrasting soil profile. It refers clearly to a layered soil profile: clay over sand. Clay topsoil is characterized by good soil fertility, and favourable water availability, though not entirely easily extractable. On the negative side, heavy clay topsoil has poor internal drainage, is difficult to cultivate, and causes delays in the growing season.

Conversely, sandy soils are usually characterized by low fertility and are sensitive for nutrient leaching. Sands have poor structure which restricts root development, and have low water holding capacity, but they are well drained by their high hydraulic conductivity, and have good aeration, which in the case of this combination (with heavy clay) has an improving effect.

When the heavy clay topsoil is wet, water movements into and through the soil are slow. In regions having wet winter, the moment of soil cultivation and sowing is later in spring than on other soils. But apart from too wet, the heavy clay soil can also be too dry for good tillage, which makes the time window for soil tillage quite narrow. Indeed, once the soil is dry, the speed of drying out is accelerated, and if there is rain, the water inflow goes fast through the profile.

In addition, ploughing heavy clay soils requires more powerful machinery which may create compaction which affects the rootability and aeration of the soil, and leads to lower crop yields. The sandy subsoil may have a positive influence on the workability of the clay topsoil, as it will speed up the soil drying in spring.

Scientific rationale for the unclear synergy

Partial compensation of the mutual limitations in sand and in clay is possible, but if it happens, it may depend on many factors. In the first place, the thickness and properties of the clay layer, and the particularities of the sandy subsoil, but also other factors like precipitation regime, climatic drought, and length of growing season.

In general contrasting textural layers in the soil form obstacles for root growth, and for soil water vertical movement (upward, downward). Discontinuities in the soil cause a reduction in effective rootable soil depth and lead to lower water availability to plant roots. In any case, the sandy subsoil will retain less plant available water than a subsoil of medium or heavy texture and the vulnerability to drought will be larger. The constraint caused by sandy texture is the most severe for the 100% pure sands, but for sands with a loamy character (higher silt content) and finer sand grains the severity decreases.

The severity of the water availability constraints depends also on the depth of the groundwater table. A shallow groundwater table can compensate for lack of soil moisture by capillary rise, but in a sandy subsoil the capillary rise becomes negligible unless the groundwater level is very close under the clayey topsoil. On the other hand, the sandy subsoil may improve internal drainage, and notably contribute to speeding up the start of the growing season by diminishing the delay in cultivation and planting time.

Likely conditions where it can occur

Alluvial plains are the most likely landscape positions where clay over sand soil profiles can occur. In principle they can occur under any climatic regime.

3.3.5 Unfavourable texture and stoniness (heavy clay) × Steep slope

Agronomic rationale for the unclear synergy

For agricultural use, the steepness, regularity, shape, orientation and length of the slope are relevant for farm operations, water management and erosion risk. A steep slope makes land management difficult, especially when working with big machines, and increases the runoff.

The negative impacts of the combination of steep slope and heavy clay texture are the difficult mechanization, the shorter window for cropping or/and the larger drought risk. While the positive impacts are better external drainage and possibly warmer growing conditions (on south facing slopes).

Scientific rationale for the unclear synergy

Usually soils on steeper slopes are rather shallow, and therefore retain less moisture. They have also stronger fluctuation in the soil moisture content than related soils on flat land.

Heavy clay topsoil has a low water infiltration capacity, except possibly in long, dry periods when cracks are open. On sloping terrain, the low infiltration leads to rain water run-off, leading to a reduced recharge of soil moisture. This makes clay soils on slopes more sensitive to drought.

On the other hand, especially in periods when the rainfall is abundant, the risk of poor drainage inherent to heavy clay texture is reduced. In temperate regions, the warm south facing side of sloping terrain can make a difference in suitability for growing crops, and favour earliness of growth in late winter and spring.

How it all interacts is hard to predict, because especially on steep slopes the variation in growing conditions is high (i) due to large within field variations in soil properties (depth, organic matter, stones and gravel), (ii) due to south/north exposure, and (iii) due to variable soil.

Likely conditions where it can occur

Heavy clay soils on steep slopes originate from in situ weathering of soils from basic parent material like marl, limestone, basalt. At a European scale, their occurrence should be limited and mostly in mountain areas (Driessen et al., 2001).

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Abstract

Support for farming in areas facing natural constraints aims at compensating farmers for disadvantages due to adverse biophysical conditions. EU regulation No 1305/2013 provides grounds to delineate, amongst others, ‘areas with specific constraints’ through the combination of biophysical criteria of Annex III when at least two of the biophysical criteria are present within a margin of not more than 20% of the threshold value initially defined.

An ad-hoc panel of experts, under JRC steering, has prepared guidance and recommendations on the plausible combination of criteria and relevant sub-severe thresholds. However, the experts have also underlined the uncertainties of this exercise due to data availability and the complexity of soil-climate-plant interactions.

The eight biophysical criteria (indeed 14 sub-criteria) were cross-tabulated to examine the resulting 91 pairwise combinations. These can result in negative or positive synergies, no interaction, unclear synergy; some combinations are not possible. Moreover, specific cases were also identified where criteria combinations are not appropriate (e.g. when criteria are conceptually linked).

An assessment of the threshold values towards the 20% margin was carried-out and revealed that the application of the exact threshold value is not always possible or reasonable. As a consequence, five approaches to this situation were defined and accordingly applied to the concerned criteria. For each criterion, the rationale and justification for the sub-severe threshold application are provided in the document. For the combination of criteria, factsheets were prepared for all negative (25 cases), positive (3 cases) and unclear synergies (5 cases).

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