Authors: Peter Groot Koerkamp, Loekie Schreefel, Niko Wojtynia, Alfons Beldman, Imke de Boer, Marjolijn de Boer, Bram Bos, Marjolein Derks, Jerry van Dijk, John Grin, Antoine Heideveld, Marko Hekkert, Gerard Korthals, Jan Peter Lesschen, Annemiek Pas-Schrijver, Walter Rossing, Rogier Schulte, Bert Smit, Hannah van Zanten and Wouter-Jan Schouten
Date: January 14 2021
Status: Version 1.0

Discussion Paper

Outline of a Regenerative Agriculture System at Scale

Table of contents

1 Introduction

The Netherlands is known around the world for its highly efficient agricultural sector, with high production levels per unit of input, low resource use and low emissions and losses to the environment per kilogram of food produced. Over the last decades impressive results have been achieved in the reduction of environmental impacts .

Despite these results, Dutch agriculture faces serious challenges to achieve the sustainability goals of the UN (Sustainability Development Goals), the EU and the Dutch government with respect to planetary boundaries (climate change, biodiversity, freshwater use, nutrient cycling and losses, and land system change), as well as society (consumer and societal acceptance, risk of zoönoses). Meanwhile many farmers are facing significant challenges to earn a living income. A team of researchers from Wageningen, Utrecht and Amsterdam universities, coordinated by TiFN, is exploring how the Dutch agricultural system can become regenerative, with positive impact on nature and the living environment, and with healthy farmer business models. This team is collaborating in a public private partnership project that is funded by FrieslandCampina, Cosun, BO akkerbouw, Rabobank, Topsector Agri & Food and TiFN.

The project consists of five work packages as shown in figure 1.

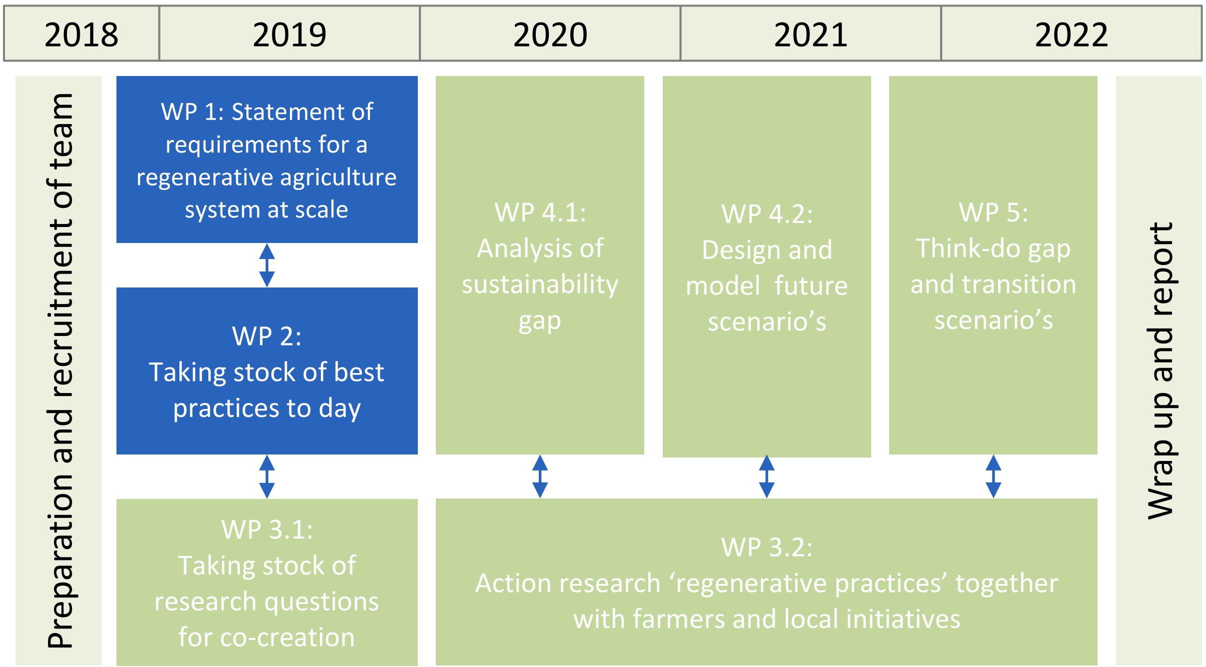


Figure 1. Project plan and work packages of the Regenerative Agriculture project.

The main deliverables of these work packages are:

1. An integrated long term (2050) outline of a regenerative agriculture system at scale, for use case area the Netherlands;
2. An assessment of the expected impact of running initiatives and existing best practices towards this integrated outline;
3. Co-creation of next practices of regenerative agriculture;
4. ‘Proof of principle’ of a regenerative agriculture system for use case the Netherlands, at scale and with sound business models: several quantified scenarios in compliance with the outline for 2050;
5. Science based and quantified transition scenario’s from the existing agriculture system towards the 2050 outline.

This outline of a regenerative agriculture system at scale is the result of the first two years of the project, and more specifically of WP 1 and 2. It aims to specify the concept of a ‘regenerative agriculture system’ i.e. to define the goals it has to achieve as precise and concrete as possible, without describing and prescribing *how* these goals should be achieved. Wherever possible the goals are quantified based on available scientific knowledge and insights. For a number of goals, science based quantification was not (yet or completely) possible; for these specific goals the quantification will follow in later releases of this document, as soon as science based quantification of boundary conditions is available.

The aim of this document is to provide an integrated and science based overview of long term objectives and boundary conditions for a regenerative agriculture system. The document as such does not provide new scientific insights on specific elements; the value is in the integration of insights from many different scientific disciplines into one logically ordered and uniformly described coherent outline.

The document will be used to evaluate and compare current agricultural practices, assess the potential impact of existing best practices and to design future scenarios in compliance with the outline. In parallel, we invite readers to provide input on this outline and collaborate with us to further build and improve it.

In addition, note that this document is meant to be a discussion paper, and does not necessarily represent the points of view of the individual project partners regarding the future of agriculture.

2 Executive Summary

Building on scientific literature we have defined regenerative agriculture as 'an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating and supporting ecosystem services, with the aspiration that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production'.

In addition to this definition at farm level we propose the following vision for a regenerative agriculture *system* at landscape or higher system levels:

A regenerative agriculture system enables production of food & biomass and enables ecosystems to maintain a healthy state and evolve, while contributing to biological diversity, integrity of the biosphere, human well-being and economic prosperity of society.

Based on this long term vision we have defined a comprehensive outline of a regenerative agriculture system that encompasses/includes all ecosystem services, soil functions and planetary boundaries. This outline covers 14 topics and describes the 'outcomes' that are needed to meet the overall objectives, without being prescriptive on 'how' these outcomes should be achieved. Therefore we use the term 'required outcomes' which precisely and quantitatively describe the target performance of the regenerative agriculture system. These 'required outcomes' are related to the inputs and use of resources, the output (food, biomass) and losses/emissions, and the preferred state of soils, water bodies, animals, biodiversity and people. The outcomes encompass environmental, social and economic aspects, and are defined at five different system levels:

- field (above and below ground),
- farm,
- local landscape (including air and water bodies)
- the Netherlands and
- international.

All required outcomes are based on and supported by scientific literature. A summary of the required outcomes is provided in table 1.

In the next phase of the regenerative agriculture project, this outline will be used to assess the potential impact of existing best agricultural practices and farmer business models that are listed in chapter 6, and to design future scenarios in compliance with the outline.

For this design of scenario's that meet all the required outcomes at the relevant system levels, we expect the need for a mosaic of innovative solutions. Some of these solutions may exist as best practices today, but most likely there will be a need to design 'next practice' solutions.

Table 1. Summary of the required outcomes of a regenerative agriculture system.

<table>
<tr><th>Ecosystem services/soil functions</th><th>Required outcomes at field and/or farm level</th><th>Required outcomes at local or higher level</th></tr>
<tr><td>1. Soil quality + fertility,</td><td>• A resilient soil food web with functional redundancy; high abundance and richness of soil micro-biome
• Resilient soil physical quality; a.o. dry bulk density < 1.6 g/cm^{-3} of dry matter
• Soil organic matter $>$ 4%-8% (soil and farm type dependent)</td><td>• No requirements in addition to field/farm level requirements</td></tr>
<tr><td>2. Primary productivity of food & nutrition, raw materials and medicinal resources</td><td>• Production of safe and high-quality food and biomass</td><td>• Average production/ha high enough to produce sufficiënt food and biomass on $<$ 11-15 M km^2 cropland, globally
• Circular system; input/output ratio of human digestible protein < 1</td></tr>
<tr><td>3. Carbon & climate regulation</td><td>• Soil organic matter $>$ 4%-8% (soil and farm type dependent)</td><td>• EU Agriculture and nature combined are a 'net carbon sink' by 2050
• In between step, deliver on commitments in climate agreement, i.e. reduce net GHG-emissions from Dutch Agri + landuse with $>$ 6 MT by 2030</td></tr>
<tr><td>4. Water purification & regulation</td><td>• Water usage $\leq$ natural available
• Water storage capacity $>$ … (soil type dependent)</td><td>• Water quality good/very good according to water framework directive
• Water surpluses are collected as buffer
• No negative impacts on water in natural areas and for local communities</td></tr>
<tr><td rowspan="2">5. Provision & cycling of nutrients
6. Local air quality</td><td colspan="2">• N and P accumulation in soils limited to levels that minimize risk of leaching and high emissions to the environment
• All N, P and micro-nutrients inputs in system come from renewable sources (air, manure or recovered from sewage/environment)</td></tr>
<tr><td>• No accumulation of Persistent organic pollutants (POPs) in soils, water or air</td><td>• Particulate matter $<$ WHO limits
• N deposition in natural habitats $<$ EU limits
• NO and NO_2 emissions within EU directives</td></tr>
<tr><td rowspan="2">7. Biological control & pollination
8. Genetic diversity,
9. Habitats for species</td><td colspan="2">• >10% of each square km landscape (public space + farmland combined) is semi natural habitat</td></tr>
<tr><td>• year-round diversity of habitat and resource provision for farmland species for all stages of the life cycle. (providing habitat for farmland species and enabling natural pest control)
• Abundance and diversity of populations for natural pest control</td><td>• Migration of species between all nature areas enabled
• Diversity of gene pool for locally well-adapted crops and farm animals
• Abundance and diversity of farm-land species and pollinators</td></tr>
<tr><td>10. Farmer income,
11. Animal welfare,
12. Attractive work,
13. Attractive landscapes,
14. Connection rural/urban</td><td>• Farmer incomes $\geq$ living income
• Farm animals have a life worth living
• Farms provide attractive and meaningful work</td><td>• Agricultural ecosystems in combination with nature provide attractive landscapes
• Good connection between rural and urban communities</td></tr>
</table>

3 Objectives of a regenerative agriculture system

Review of existing definitions in scientific literature
A literature study of all peer-reviewed articles on regenerative agriculture by Schreefel *et al.* (2020) shows that, thus far, there is no agreed common definition of regenerative agriculture nor of its objectives. Most definitions rather describe aspirations and activities of regenerative agriculture at farm and/or local level. Quantified objectives for outcomes as well as aspirations for a regenerative system at larger scales are lacking.

However, from the literature study there appears to be convergence between definitions regarding the environmental pillar of sustainabillity at farm level (see figure 2). All definitions mentioned objectives and/or practices to reduce environmental externalities and specificly about soil related issues. Objectives above farm level and aspirations regarding socio-economic aspects were found, but without associated operationalisation into specific activities. The articles found in literature desribe regenerative agriculture as a nature-based farming approach in which the entry point is soil health and it stimulates a system change in which primary productivity should be in balance with is ecological and humanistic surroundings. In this outline of a regenerative agriculture system we will build on this common thread in the literature on regenerative agriculture, elaborate and expand it, and propose a vision, together with quantified required outcomes of a regenerative system, when it is implemented in practice at a large scale.

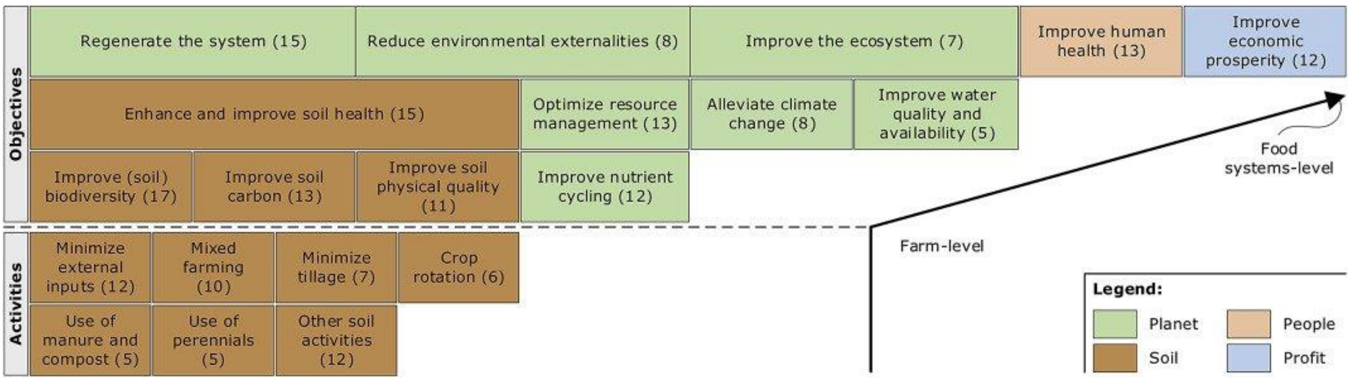


Figure 2 Boxes with the core themes of regenerative agriculture, categorized (indicated by colors) according the three themes/pillars of sustainability and soil; 'the number between brackets' represents the number of peer-reviewed articles referring to each theme (Schreefel et al., 2020).

Vision:
Building on this literature review we defined the following definition of regenerative agriculture as formulated by Schreefel *et al.*:

An approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating and supporting ecosystem services, with the aspiration that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production.

In addition to this definition at farm level we propose the following vision for a regenerative agriculture *system* at landscape or higher levels:

A regenerative agriculture system enables production of food & biomass and enables ecosystems to maintain a healthy state and evolve, while contributing to biological diversity, integrity of the biosphere, human well-being and economic prosperity of society.

Explanation and justification of the formulation of this vision:
Most existing agriculture systems are organized with the aim to maximize efficiency per unit of input (energy, nutrients, labour, land), thereby minimizing land use footprint and negative impacts per kilogram of produced food and biomass[1]. Across the globe, impressive efficiency gains have been achieved towards this aim: the global crop production index has grown almost 300% since 1960[2], while arable land area increased with no more than 12%[3]. Land use footprint per kilogram of produced food and biomass has thus been reduced with over 70%. These efficiency gains were essential to feed the growing world population. Despite these efficiency gains however, food production contributes significantly to the exceedance of planetary boundaries.[4] In order to produce the amount of food that is needed for today's world population within planetary boundaries, many sustainable agriculture efforts are aimed at optimizing the current systems and gradually trying to comply to stricter conditions on e.g. inputs and emissions/losses. Current production systems however, do have their limitations in reaching these stricter conditions and better performance, and many trade-offs are encountered; improvements on one aspect lead to negative side-effects and lower performance on another aspect.

We think that it is no longer enough to minimize land use footprint and negative impacts per kilogram of produced food and biomass. We therefore propose with our vision that the aim of agriculture systems needs to be broadened from 'maximizing production and efficiency' towards 'reaching the goals of food and biomass production, and at the same time contributing positively to biosphere integrity, human well-being and economic prosperity'. This vision addresses all three pillars of the People-Planet-Profit concept, and many Sustainable Development Goals (SDG's) and specific targets of the UN (see appendix 3).

To deliver on the vision we propose three overarching objectives for a regenerative agricultural system:

A. Natural Capital Stocks: all natural capital stocks used in agricultural systems are regenerated to and subsequently maintained above threshold levels that are required for a resilient agro-ecosystem i.e "a system that has the capacity to recover from disruption of functions, and the mitigation of risks caused by disturbance" (Jackson, Pascual and Hodgkin, 2007);
B. Natural Capital Flows: the biophysical conditions and processes in the agro-ecosystem allow that all ecosystem functions[5] and ecosystem integrity in agricultural areas are enabled perpetually[6] ;
C. Impact beyond agriculture: The agro-ecosystem has neutral or positive impact and causes limited risks on natural capital stocks in natural ecosystems outside the agricultural ecosystem, and on health and well-being in human settlements and public spaces.

---

[1] de Boer, I.J.M. and M.K. van Ittersum, 2018. Mansholt lezeing 2018 - Circularity in agricultural production.
[2] Worldbank: https://data.worldbank.org/indicator/AG.PRD.CROP.XD
[3] Worldbank: https://data.worldbank.org/indicator/AG.LND.ARBL.ZS
[4] See for example Eat-Lancet, 2019: https://eatforum.org/eat-lancet-commission/eat-lancet-commission-summary-report/
[5] See list in appendix 1
[6] A and B are interdependent (no B without A, and B is required for A)

4 Different scales in the biophysical system

To define the required outcomes that are needed to meet these overarching objectives we need to first define the relevant systems, subsystems and the elements in the system (objects / subjects), and with that the various system levels. Figure 3 provides a visualization of the system levels that are relevant for defining required outcomes of a regenerative agriculture system. This visualization helps to distinguish various system boundaries, scales or levels within the system and attribute the goals per system level. This figure does not represent any relationships, flows of energy, mass or information between the subsystems. This figure only describes the levels in the biophysical system and does not represent any socio-economic aspects.

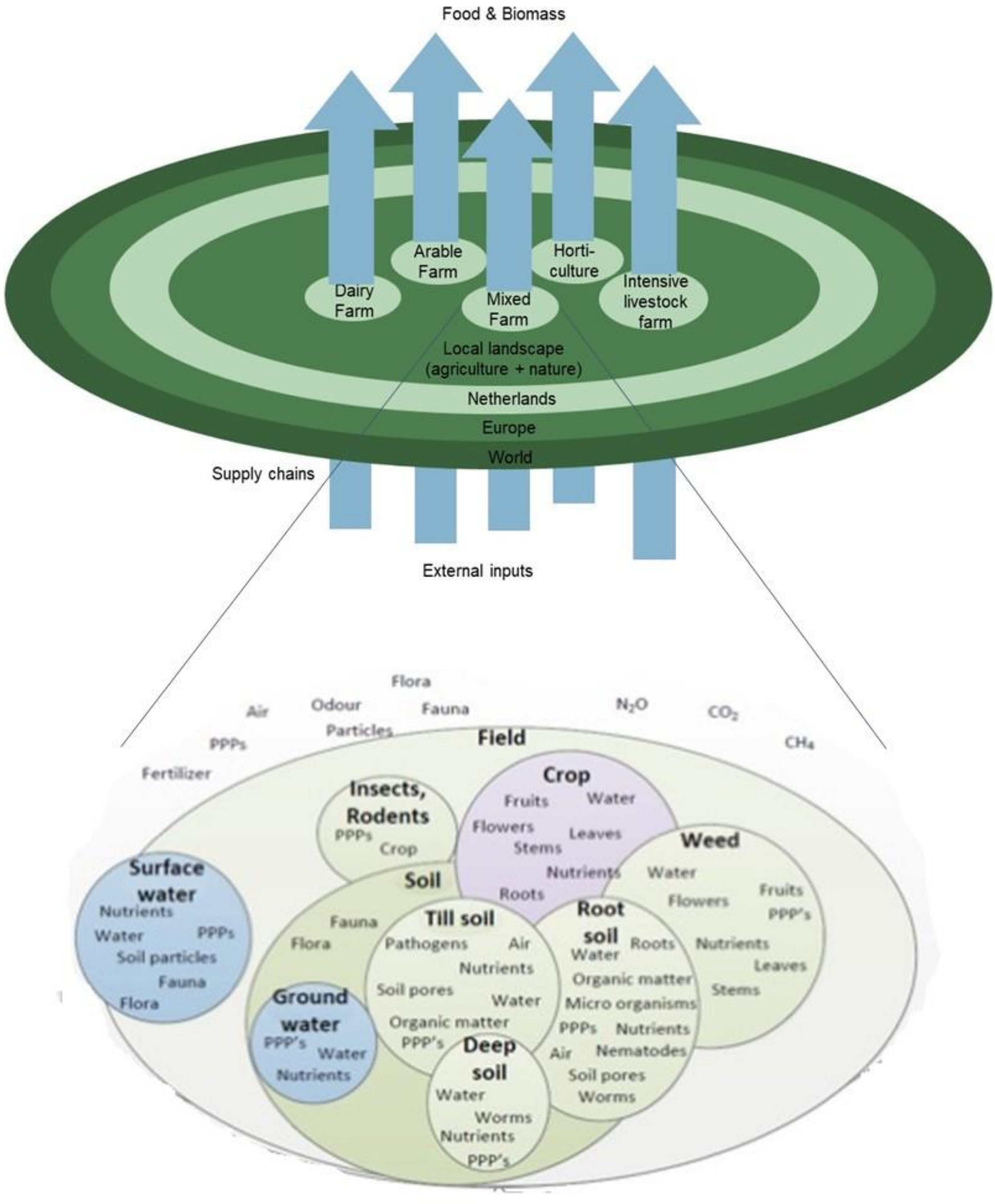


Figure 3 Visualization of the biophysical system boundaries and the subsystems, subjects (living) and objects (non-living) that are relevant for a regenerative agriculture system

5 Required outcomes of a regenerative agriculture system

To meet the objectives of a regenerative agriculture system at the relevant system levels, we have defined required outcomes at each of these system levels. These required outcomes link to various aspects and describe what is needed to meet the overall objectives, without being prescriptive on how these outcomes should be achieved. Therefore we use the term 'required outcomes'. In addition it needs to be noted that we do not expect that individual farms can meet all the outcomes. For a regenerative system at scale there will be a need to create symbiotic mixes of a diversity of farming systems, as well as nature, that as a mosaic generate a net outcome that meets all the requirements at the appropriate scales, e.g. regional scale for ammonia emissions and (inter-)national scale for GHG emissions.

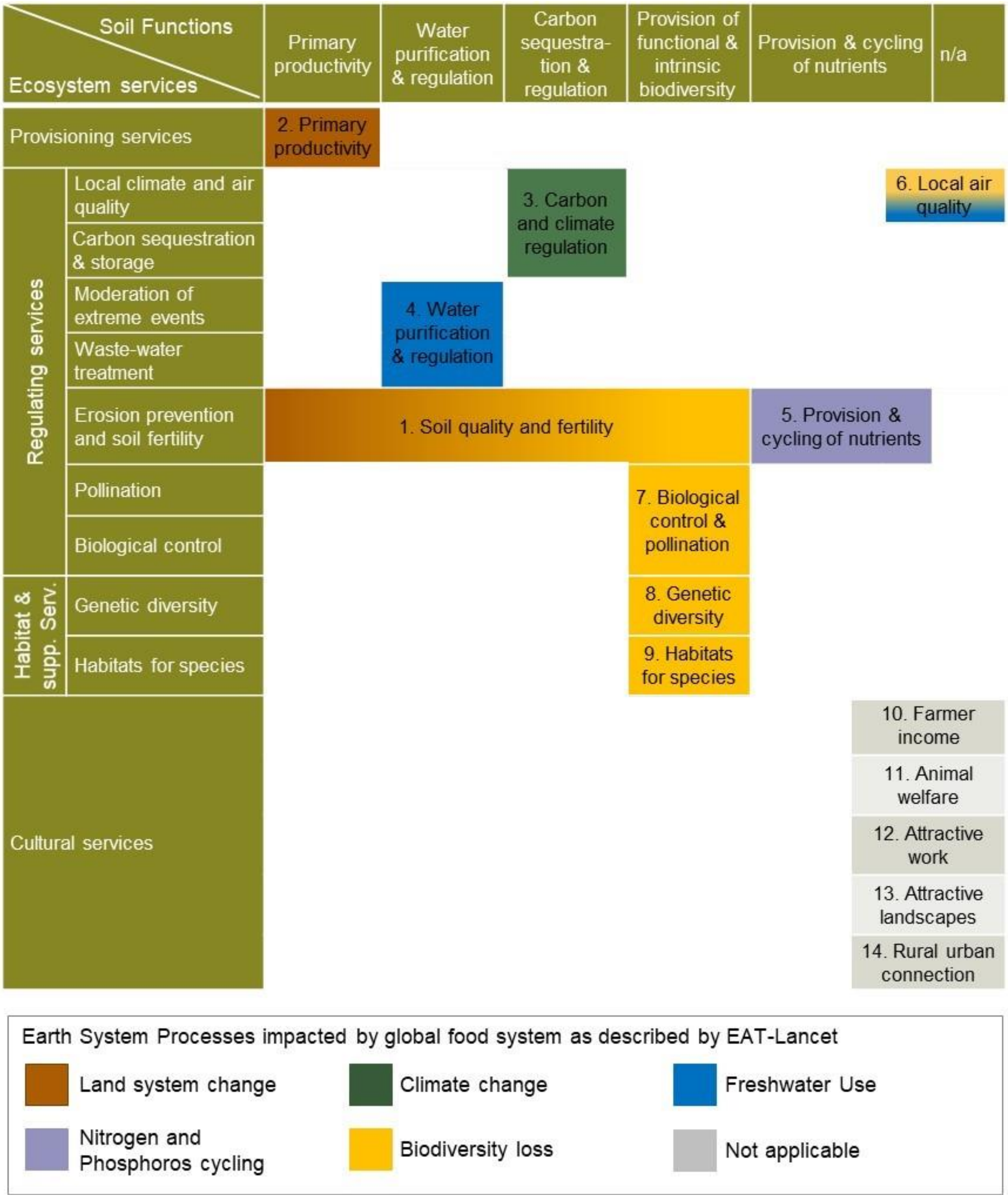


Figure 4. The fourteen identified topics for the outline of a regenerative agriculture system plotted against the five soil functions of the Landmark Study (horizontal axis; see appendix 1), the ecosystem services according to TEEB[3] (vertical axis) and linked to the planetary boundary targets from EAT-Lancet (in color, see legend).

The list of required outcomes that we propose is developed by combining the objectives that are described by Schreefel *et al.* with three existing frameworks: the list of ecosystem services according to TEEB[7], the planetary boundary targets from EAT-Lancet and the soil functions in the Landmark study (see appendix 1). By combining these existing frameworks we identified fourteen topics on which we need to define required outcomes and conditions (see figure 4):

Biophysical outcomes and conditions of a regenerative agiculture system:

1. Soil quality and fertility (soil biodiversity, soil structure and soil organic matter);
2. Primary production of food and biomass;
3. Carbon and climate regulation;
4. Water purification and regulation;
5. Provision and cycling of nutrients;
6. Local air quality;
7. Biological control and pollination;
8. Genetic diversity (diversity of species, abundance of species and genetic diversity within populations)
9. Habitats for species;

Required socio-economic outcomes

10. Farmer income;
11. Animal welfare & health;
12. Attractive work;
13. Attractive landscapes;
14. Rural – urban connection;

On each of these fifteen topics we distinguished and defined required outcomes at relevant system levels as described in figure 3.

In formulating these required outcomes we aim to combine the best available scientific insights. Most notably we built on the following sources:

- the extensive work that has been done with the development of the soil navigator DSS: this is a decision support system (DSS), developed by Debeljak *et al.* (Debeljak et al., 2019[8]). The soil navigator is based on a qualitative multi-criteria decision analysis that has been applied using the Decision EXpert (DEX) integrative modelling methodology. Five teams of scientific experts from across Europe have structured, calibrated and validated DEX models for the five soil functions: primary productivity (Sanden et al., 2019)[9], water purification and regulation (Wall et al, in press), carbon sequestration and climate regulation (Van den Broek et al., 2019)[10], nutrient cycling (Schroder et al., 2016)[11] and biodiversity and habitat provision (Van Leeuwen et al., 2019)[12]. More information about the Soil Navigator can be found in annex 2 and on http://www.soilnavigator.eu/

[7] The Economics of Ecosystem services and Biodiversity, http://www.teebweb.org/

[8] Debeljak M, Trajanov A, Kuzmanovski V, Schröder J, Sandén T, Spiegel H, Wall DP, Van de Broek M, Rutgers M, Bampa F, Creamer RE and Henriksen CB (2019) A Field-Scale Decision Support System for Assessment and Management of Soil Functions. Front. Environ. Sci. 7:115. doi: 10.3389 / fenvs.2019.00115

[9] Sanden, T., Trajanov, A., Spiegel, H., Kuzmanovski, V., Saby, N., Picaud, C., ... & Debeljak, M. (2019). Development of an agricultural primary productivity decision support model: a case study in France. Frontiers in Environmental Science, 7, 58.

[10] Van de Broek, M., Henriksen, C. B., Bhim, G. B., Lugato, E., Kuzmanovski, V., Trajanov, A., ... & Creamer, R. (2019). Assessing the climate regulation potential of agricultural soils using a decision support tool adapted to stakeholders' needs and possibilities. Frontiers in Environmental Science, 7, 131.

[11] Schröder, J. J., Schulte, R. P. O., Creamer, R. E., Delgado, A., Van Leeuwen, J., Lehtinen, T., ... & Wall, D. P. (2016). The elusive role of soil quality in nutrient cycling: a review. Soil Use and Management, 32(4), 476-486.

[12] van Leeuwen, J., Creamer, R., Cluzeau, D., Debeljak, M., Gatti, F., Henriksen, C., ... & Saby, N. (2019). Modeling of soil functions for assessing soil quality: soil biodiversity and habitat provisioning. Frontiers in Environmental Science, 7, 113.

- The application of the Soil navigator to map competing expectations of agricultural soils in Europe (Schulte et al., 2019)[13]
- The work by de Boer et al. and van Zanten et al. on circular food systems[14]. (https://www.circularfoodsystems.org)
- The work by by many scientists across Europe in the development of the EU Water framework directive[15]
- The work by Lesschen et al, supporting the Dutch climate agreement[16]
- The biodiversity monitors that have been developed for Dairy farming[17] (2018) and Arable farming[18] (2020)

By combining all these sources, we propose the following nine required outcomes with respect to the biophysical topics (all soil functions, covering provisioning ecosystem services, regulating ecosystem services and habitat services):

1. **Maintenance of soil quality and fertility**
   As described in the literature review by Schreefel et al., maintenance of soil health is the basis of a regenerative agriculture system. Specifically on soil we distinguish three required outcomes that are based on the soil related aspirations in scientific literature on regenerative agriculture (see figure 2):
   a. Soil biodiversity: A resilient soil food web with functional redundancy.[19] [20] This requires sufficient density and diversity of important members of the soil food web in order to ensure the required level of functional traits, like decomposition, respiration etc.
      A quantified requirement on soil biodiversity is not available (yet). As measurable requirement we propose soil navigator (see above) DEXscore 'high' on provision of functional and intrinsic biodiversity (system level: field). This is an aggregated indicator based on the following underlying indicators: enchytraeid abundance, enchytraeid richness, microathropod abundance, microathropod richness, nematode abundance, nematode richness, earthworm abundance, earthworm richness, fungal bacterial biomass ratio, fungal biomass and bacterial biomass.
   b. Soil physical quality: Crops are tilled in the top soil (0-30 cm depth), but problems with physical soil quality generally appear in the top layer of the subsoil, where the plough pan is formed. Physical soil qualtiy can be expressed with the following soil characteristics of the subsoil, according to [21]: packing density (g.cm$^{-3;}$ closely related to dry volume weight), pore volume (%), air filled pore volume (%), saturated water permeability (cm.day^{-1}), and penetrometer resistance (MPa). Good physical soil quality means that subsoils are not compacted, and the water holding and infiltration capacity is high. Compacted soils with higher bulk densities have in general less

---

[13] Schulte, R. P., O'Sullivan, L., Vrebos, D., Bampa, F., Jones, A., & Staes, J. (2019). Demands on land: Mapping competing societal expectations for the functionality of agricultural soils in Europe. Environmental Science & Policy, 100, 113-125.
[14] Van Zanten, H. H. E., Van Ittersum, M. K., & De Boer, I. J. M. (2019). The role of farm animals in a circular food system. *Global Food Security*, *21*, 18-22.
[15] https://ec.europa.eu/environment/water/water-framework/index_en.html
[16] Lesschen, J.P., Reijs, J., Velling, T., Verhagen, J. Kros, H., de Vries, M., Jongeneel, R., Slier, T., Gonzalez Martinez, A., Vermeij, I., Daatselaar, C., 2020. *Scenariostudie perspectief voor ontwikkelrichtingen Nederlandse landbouw in 2050. Wageningen Environmental Research Rapport 2984.*
[17] See: http://biodiversiteitsmonitormelkveehouderij.nl/ and
[18] See: https://bo-akkerbouw.nl/NL/diensten/Actieplan_Plantgezondheid/Biodiversiteitsmonitor
[19] Van den Elsen, E., Knotters, M., Heinen, M. Römkens, P., Bloem, J.,Korthals, G. 2019: Noodzakelijke indicatoren voor de beoordeling van de gezondheid van Nederlandse landbouwbodems
[20] Rutgers et al. 2007: Typeringen van bodemecosystemen in Nederland met tien referenties voor Biologische bodemkwaliteit
[21] J.J.H. van de Akker and W.J.M. Groot, 2008. Een inventariserend onderzoek naar de ondergrondverdichting van zandgronden en lichte zavels. Alterra rapport 1450.

pores/ aeration, lower water holding and infiltration capacity, increased resistance for root growth, reduced earthworm population, reduced nitrifying bacteria populations, increased dentrifying bacteria population. This all affects all soil functions negatively.
Like with soil biodiversity, a quantified requirement on all relevant elements of soil structure is not available (yet). We therefore propose two measurable requirements (system level: field):
   i. dry bulk density of the subsoil as critical physical soil quality indicator, which should be below the norms in table 2.
   ii. DEXscore 'high' on the relevant indicators in the Soil navigator, which are: soil bulk density, artificial drainage, irrigation, hydragric/irragic horizon, groundwater table depth, soil texture and vertic/fragic horizon

c. Surfficient oil organic matter is important for and supports soil biodiversity and physical soil quality[22]. We therefor set a minimum level of soil organic matter per soil type and use as mentioned in the table 2 [23,24]. Besides the organic matter content also the quality of the organic matter is relevant, but this could not yet be expressed in clear required outcomes.

Table 2 Minimum or maximum values for soil density and organic matter for three main soil types in the Netherlands.

	Peat	Clay		Sand	
		cropland	Permanent grassland	cropland	Permanent grassland
Dry bulk density of subsoil ($g\ cm^{-3}$ of dry matter)[25]	<1.6	<1.6	<1.6	<1.6	<1.6
Soil organic matter[26] content (%)	n/a	>4	>8	>4	>6

2. **Primary production**
Quantity and quality of agricultural production is sufficient[27] to serve the needs[28] for food and biomass:
   a. European average production of food, feed & biomass per hectare is sufficient to serve the needs of the European population without expansion of agriculture area.

[22] In international literature there is not a clear consensus on a critical limit, often 1% or 2% of soil organic carbon is mentioned, see e.g. Loveland, P., Webb, J., 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. Soil and Tillage Research 70, 1-18.
[23] Lesschen, J.P., Vellinga, T., Dekker, S., van der Linden, A., Schils, R.L.M. 2020. Mogelijkheden voor monitoring van CO_2-vastlegging en afbraak van organische stof in de bodem op melkveebedrijven. Wageningen Environmental Research, Rapport 2993.
[24] Conijn, J.G. and J.P. Lesschen, 2015. Soil organic matter in the Netherlands; Quantification of stocks and flows in the top soil. Alterra report 2663 / PRI report 619. Wageningen UR, Wageningen.
[25] For sandy and sandy loam soils (clay conent < 16.7%), this threshold is represented by the dry bulk density threshold value for subsoils of Db = 1.6 $g\ cm^{-3}$, a Dutch threshold value where the packing density threshold is not exceeded. For soils with a clay content > 16.7% the packing density threshold (PD = 1.75 $g\ cm^{-3}$) is expressed in a dry bulk density threshold of (1.75 - 0.009 *clay content) $g\ cm^{-3}$.
[26] See also, Oldfield, E. E., M. A. Bradford and S. A. Wood (2019). "Global meta-analysis of the relationship between soil organic matter and crop yields." SOIL **5**(1): 15-32.
[27] Sufficient will be defined and quantified later in the project when WP 3.1 is finalized. We will then choose one or more of the following options: a) use existing scenario studies, b) minimum nutritional need, c) target mix of protein sources that minimizes feed vs food competition, and d) existing produc-tion levels + expected % population growth. For now we will first model a system that meets all other required outcomes and assess how much food & biomass can be produced in such a system
[28] See also a recent analysis on the demand for food, feed, fibre and (bio)fuel for EU member states: https://www.sciencedirect.com/science/article/pii/S1462901119301443

b. No negative impact on landuse change outside the Netherlands. The global agricultural area is not expanded and global crop land area kept below < 11-15 M square km[29] (system level: Global)
c. A circular production system that minimizes competition between food, medicines, biobased materials, feed and energy[30]
    i. For animal based products: input/output ratio of human digestable proteins < 1;
    ii. For biomass: no use of biomass that leads to competition with food, feed or medicines production;
    iii. For energy: no use of biomass that leads to competition with food, feed, biomass and medicines production;
    iv. Minimized waste of produced biomass at all stages from production to consumption;
    v. Maximized recovery of nutrients from human feces and remaining food wastes.

3. Carbon storage and greenhouse gas emissions

Emissions and losses of methane (CH_4), nitrous oxide (N_2O) and carbondioxide (CO_2) from farming processes and land use contribute to global warming and consequently climate change. In 2016 the emissions by Dutch agriculture amounted to 35 Mton $CO_{2\text{-eq.}}$, comprising of[31]:

- CH_4 and N_2O from dairy farming (12.2 Mton CO_2-eq., 35%),
- CO_2 from greenhouse horticulture (7.4 Mton, 21%),
- CO_2 from agricultural landuse (LULUCF, 7 Mton, 20%)
- CH_4 and N_2O from pigs and other animal husbandry (5.5 Mton CO_2-eq.,16%),
- CH_4 and N_2O from arable farming & horticulture (1.4 Mton CO_2-eq.,4%)
- and CO2 from tractors and agricultural machinery (1.2 Mton, 3%).

In addition to the greenhouse gas emissions emitted in the Netherlands, another 15.5 Mton CO_2-eq. of methane, nitrous oxide and carbondioxide are emitted elsewhere in the world for cropping feed ingredients for livestock in the Netherlands [32].

In order to mitigate climate change, both reduction of emissions as well as additional storage of carbon is required. The following outcomes need to be achieved:

a. Agriculture and nature combined are a net carbon sink, i.e. carbon capture in soils, permacultures and forests exceed CO_2-eq of all greenhouse gas emissions (CH_4, N_2O and CO_2 combined)[33] (system level: all land use Europe, including nature areas).
b. As an in between step towards the long term target 3b. it will be required to deliver on the commitments as signatory to the Paris Climate Agreement. Economy wide commitments are made that are adding up to 49% reduction of GHG emissions versus 1990 by 2030[34] (system level: Netherlands, all sectors combined). This has been further translated to emission reduction target of 3.5 MT and ambition of 6 MT

[29] Food Planet Health (Eat-Lancet, 2019);https://eatforum.org/content/uploads/2019/07/EAT-Lancet_Commission_Summary_Report.pdf, see also figure 6 in annex 1
[30] See van Zanten et al., 2019
[31] PBL, balans van de leefomgeving 2018; Landbouw en voedsel - Balans van de Leefomgeving 2018 - PBL Planbureau voor de Leefomgeving
[32] Vellinga, Th.V., Reijs, J.W., Lesschen, J.P., Van Kernebeek, H.R., 2018. Lange termijn opties voor reductie van broeikasgassen uit de Nederlandse landbouw, een verkenning. Wageningen Livestock Research, Rapport 1133.
[33] Ambition mentioned in the vision 2050 for agriculture and landuse in Dutch Climate Agreement. Further research needed to determine whether this requirement needs to be fulfilled on system level Netherlands or higher on level (North West) Europe
[34] Dutch climate agreement

CO_2-eq. by 2030 for Dutch agriculture and landuse, comprising of an emission reduction target of at least 1 MT CO_2-e of methane from livestock, 1 MT from peat soils and 0.5 MT of soil carbon sequestration by 2030[35] (system level: Netherlands).

4. Water quality and quantity

Water quality refers to the chemical, physical and biological quality of ground and surface water bodies. The EU Water Framework Directive (WFD, see [36]) and EU Nitrate Directive (ND, see [37],) are used to set the required outcomes for a regenerative agriculture system in order to safeguard human health (amongst others through drinking water quality) and protect natural ecosystems. Management of quality and quantity of water bodies in the Netherlands is governed by regional water boards and many (economic) activities have their impact on them. Ecosystems and natural processes in especially soils can substantially contribute to water purification and water regulation, and is seen as an ecosystem service. We defined the following required outcomes:

a. Agricultural practices have impact on the water quality through losses of nutrients, residues of pharmaceuticals and plant protection products (herbicides, pesticides, fungicides). In a regenerative agriculture system the water quality of all (being 715 designated ones in NL) water bodies in the Netherlands is assessed as 'good' according to the Water framework directive (WFD) with respect to the chemical and ecological goals (system level: local agriculture+nature), while the impact of agriculture on achieving this goal is neutral or positive.
The assessment of ecological state of water bodies in the WFD is mainly based on the 'biological quality', which is based on algae, macro fauna, fish and water plants. The biological quality is evaluated as 'good' if all four have a score of good (one-out, all-out principle; van Gaalen et al., 2015 [38]). The EU WFD demands that in 2027 all water bodies have the status 'good' or 'very good' with respect to ecological quality, or have measures in place to reach that goal in 2050. The WFD is a European wide instrument, and takes into account national and local situations, so goals and norms are context specific. In those cases where other sources than agriculture have a major contribution on the water quality (e.g. background emissions), goals for agriculture are made context specific (e.g. have its share in reaching the goals). For more details for the Netherlands see Groenendijk et al. (2016) [39].
The goals of the WFD were taken as leading outcomes for a Regenerative Agriculture system as this defines a common scientifically underpinned approach to good water qualtiy. However, one needs to be aware that in a number of cases context specific norms in the WFD have been adjusted (read: lowered) based on political, feasibility and economic arguments, and norms for such local situations may not be enough for a truly regenerative system. Scientific projects to improve and align the monitoring and evaluation systems used in the EU member states have been carried out (http://www.aqem.de/, http://www.eu-star.at/, http://www.wiser.eu/).

b. Nitrogen loss in the form of nitrate from soils is inevitalbe in case of agricultural land use. We defined specific outcomes for nitrate concentrations in ground and open water bodies as agriculture is a major source of nitrate by leaching. Precise scientific

[35] Dutch climate agreement; table C4.2.1. In addition to the targets mentioned there are targets of 1.8-2.9 MT for greenhouse horticulture (all energy related) and about 0.6 MT for carbon sequestration in nature, but those are less relevant for this outline

[36] https://ec.europa.eu/environment/water/water-framework/index_en.html

[37] https://ec.europa.eu/environment/water/water-nitrates/index_en.html

[38] Gaalen, F. van et al. (2015), Waterkwaliteit nu en in de toekomst. Eindrapportage ex ante evaluatie van de Nederlandse plannen voor de Kaderrichtlijn Water (rapport 1727). Den Haag: PBL.

[39] Groenendijk, P., E. van Boekel, L. Renaud, A. Greijdanus, R. Michels, T. de Koeijer, 2016. Landbouw en de KRW-opgave voor nutriënten in regionale wateren; Het aandeel van landbouw in de KRWopgave, de kosten van enkele maatregelen en de effecten ervan op de uit- en afspoeling uit landbouwgronden. Wageningen, Wageningen Environmental Research, Rapport 2749

underpinning of in all respect safe nitrate levels in ground water was hard to find, and will be location and time dependent. Also, underpinning for specific levels in a Regenerative Agriculture system were not found. For practical reasons we therefor choose to take over the generic maximum nitrate levels in the EU regulation of the Nitrates Directive, being 50 mg/l.

c. The amount of water used for agricultural production (either green water – rain – for field crops, or blue water for e.g. irrigation and drinking water for animals or grey water resulting from pollutant control), is lower or equal to the amount of water that can be harvested (system level: farm / regional). This water balance may be levelled over max. 3 years, which means that water surpluses are collected (regionally/per waterboard region/ per stream area) as a buffer for drier times.
d. Water buffers (ground and open water) are restored and maintained at a level that allows for long term agricultural production.
e. Water management in agricultural ecosystems have a neutral or positive impact on water management in Natura 2000 area's and for local communities. (system level: local agriculture+nature) (see also requirement 9d.ii)

5. Nutrients and micro nutrients

Macro nutrients (nitrogen N, potassium K), meso nutrients (calcium Ca, magnesium Mg, phosporus P, sulfur S) and micro nutrients (or spore elements; main ones are boron, cupper, iron, manganese, molybdenum and zinc) are essential for life of plants, animals and humans, and they are elements of biomass produced for food, feed and biomaterials [40]. Provision and cycling of nutrients (endless reuse) is very important and can be arranged by nature (ecosystem service) and/or by human management and technology. In this outline we focus on the two most important mineral nutrients, being nitrogen and phospohorus, and micro nutrients in general. We propose the following requirements:

a. Both arable and livestock farms produce edible and other products and animals that contain nitrogen (N, mostly in the form of proteins) that leave the farm. Besides that, nitrogen can be lost to the 'environment' during farming processes in various forms (ammonia NH_3/NH_4^+; nitrite/nitrate $NO_2^-/NO3^-$; nitrogen gas N_2), and through various processes: leaching to deeper water layers, runoff from soil to ditches, leakage from e.g. manure pits, and emission to the air. Finally, not all nitrogen present is available and accessable for plants and animals in the farming systems. Nitrogen can also accumulate in the soil, in various states and levels of accessability for plants. The required outcomes on provision and cycling of nitrogen are:
    i. The amount of nitrogen lost during these production processes on the farm and accumulated in the soil can only be compensated for with nitrogen from renewable resources. The following sources are identified as renewable: dinitrogen gas fixed by plants (e.g. legumes) or emission free technology, sludges, animal slurry & manure, compost, other biomass waste streams and past N-losses accumulated in the bedding of ditches, rivers and oceans.
    ii. Accumulation of N in soils should be limited to a level based on a minimum risk of leaching depending on soil type and local conditions, and/or a minimum risk for high impact on the environment through emissions (levels defined under number 6). From the point of nutrient recycling there is no maximum amount of renewable N that can be input to a regenerative farm, as long as the accumulation in the soil poses only a minimum risk for the environment.
b. Both arable and livestock farms produce edible and other products and animals that contain phosphorus (P) and that leave the farm. Besides that, phosphorus can also

[40] de Haes, H.A.U., R.L. Voortman, T. Bastein, D.W. Bussink,C.W. Rougoor, and W.J. van der Weijden, 2012. Schaarste van micronutriënten in bodem, voedsel en minerale voorraden - Urgentie en opties voor beleid. Platform Landbouw, Innovatie en Samenleving.

be lost to the 'environment' as phosphate (P_2O_5, or otherwise) through leaching (to deeper water layers), runoff (from soil to ditches), and leakages (e.g. manure from pits), and not being available and accessable for plants and animals in the farming system. Phosphorus can also accumulate in the soil, in various states and levels of accessability for plants. The required outcomes on provision and cycling of phosphorus are:

i. The amount of phosphorus lost during production processes on the farm and accumulated below the rooting zone in the soil can only be compensated with phosphate from renewable resources. The following sources are identified as renewable: sludges, animal slurry & manure, compost, other biomass waste streams and past phospohurs losses accumutated in the bedding of ditches, rivers and oceans.
ii. Accumulation of P in soils should be limited to a level based on a minimum risk of leaching depending on soil type and local conditions. There are various ways to enhance availability of P for plants, but not considered for this outline. From the point of nutrient recycling there is no maximum amount of renewable P that can be input a regenerative farm, as long as the accumulation in the soil poses only a minimum risk for the environment.

c. Micro nutrients and potassium are very relevant and important for soil quality, plant growth and nutritional quality of the food. The required outcomes are that the availability of micro-nutrients in soils are not limiting plant growth and have no adverse effects on the soil quality (either in agricultural or natural systems), and that concentration/amount in food and feed (nutritional quality) do not lead to deficieny related diseases in human and animals. The demand for micro-nutrients is quite crop specific [41] and both demand and availabilty also depends on other soil properties, e.g. amount of other potentially limiting nutrients and carbon the soils[42]. We have therefore not set nutrient specific requirements for soil and food/feed. Shortages in the soil for micro nutrents are not expected for the short term in the Netherlands, but are predicted for the longer term for zinc and selenium because of limited supply from natural sources/mines [40]. The additional required outcome on provision and cycling of micro-nutriënts is that micro-nutrients taken from the soil by food production should be in balance with renewal of plant available stocks by natural weathering rates. If that is not possible, shortages can only be compensated with micro-nutriënts from renewable resources. The following sources are identified as renewable: sludges, animal slurry & manure, compost, other biomass waste streams and past losses accumulated in the bedding of ditches, rivers and oceans.

6. **Local air quality**

The quality of air is relevant for the agricultural production environment, the human living environment, and the flora & fauna in designated areas. Humans and ecosystems can be adversely affected by exposure to air pollutants in ambient air. The European Union has developed health-based standards and objectives for a number of pollutants present in the air, the most important being PM (particulate matter), ozone (O_3), nitrogen dioxide (NO_2), benzo(a)pyrene, and sulphur dioxide (SO_2). The complete list with standards and objectives can be found at this website of the EU [43]. These standards apply over differing periods of time because the observed health impacts associated with the various pollutants occur over different exposure times. The latest EU inventory report on air quality and its impact on human health and ecosystems was published as (EEA, 2018)

[41] see for example analysis report: https://www.eurofins-agro.com/uploads/downloads/Voorbeeldverslagen/NL_AT_klei_110506_jr_18_19.PDF
[42] Marschner's Mineral Nutrition of Higher Plants, 3rd Edition, 2011
[43] https://ec.europa.eu/environment/air/quality/standards.htm

[44]. For the most important air quality parameters relevant for agriculture, we specified detailed information and required outcomes below.

a. Particulate matter: PM2.5 and PM10 concentration in ambient air are below WHO (World Health Organisation) limits: (system level: local) Ambient PM concentration is caused by various sources and at different system levels due to (transboundary) transport in the air. Particulate matter (PM) has a wide range of health effects but are predominantly to the respiratory and cardiovascular systems. The risk for various outcomes has been shown to increase with exposure and there is little evidence to suggest a threshold below which no adverse health effects would be anticipated. The epidemiological evidence shows adverse effects of PM following both short-term and long-term exposures. As thresholds have not been identified, it is unlikely that any standard or guideline value will lead to complete protection for every individual against all possible adverse health effects of particulate matter (taken from WHO, 2005 [45]; also for scientific underpinning of the threshold values). For a regenerative agriculture we propose to follow the WHO threshold values:
   - 24-h mean PM10: 50 μg/m^3 (0.050 mg/m^3);
   - Annual mean PM10: 20 μg/m^3 (0.020 mg/m^3)
   - 24-h mean PM2.5: 25 μg/m^3 (0.025 mg/m^3)
   - Annual mean PM2.5: 10 μg/m^3 (0.010 mg/m^3)

   These WHO standards for the 24-h means for PM10 and PM2.5 are more stringent than those given in the European Air Quality Directive 2008/50/EC of May 21, 2008, Appendix XI: PM10 limit values for the ambient air. The Netherlands does not comply with EC Directive, neither with the WHO threshold values. PM in the Netherlands is generated by various natural sources (about 50% of total; e.g. sea salt and from soils) and anthropogenic sources (also about 50%). Industry, transport and agriculture, especially livestock houses, are responsible for respectively approximately 40%, 40% and 20% of the anthropogenic PM emissions in the Netherlands. Due to spatial concentration of pig and poultry farms, the local/regional contribution to the increased PM concentrations is much higher than 20% [46].
b. Air pollution contributes to the excess of nutrient nitrogen, as the nitrogen emitted to the air as NOx and NH_3 is deposited on soils, vegetation surfaces and waters. An excess of nutrients in the soil or water is referred to as *eutrophication*, which has several impacts on terrestrial and aquatic ecosystems, including threatening biodiversity (for more information, see EEA, 2016). The emission of nitrogen and sulphur into the atmosphere creates nitric acid and sulphuric acid, respectively. The fate of a great amount of these airborne acids is to fall onto the earth and its waters as acid deposition, reducing the pH level of soil and water, and leading to acidification. Acidification damages plant and animal life, both on land and in water. Ammonia and other gases can also be precursors in the formation of PM through chemical reactrion in the air (and then should comply to secton 6a). Eutrophication and acidification effects due to deposition of air pollution are evaluated using the 'critical load' concept. This term describes the ecosystem's ability to absorb eutrophying nitrogen pollutants and acidifying pollutants deposited from the atmosphere, without the potential to cause negative effects on the natural environment. Exceedances of these spatially determined critical loads present a risk

[44] European Environment Agengcy, 2018. Air quality in Europa – 2018 report.
[45] WHO, 2005. WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, Global update 2005, Summary of risk assessment. WHO technical report WHO/SDE/PHE/OEH/06.02
[46] Infomil, 2020. https://www.infomil.nl/onderwerpen/landbouw/stof/handreiking-fijn-1/sitemap/fijn-stof/. Assessed 25 September 2020.

of damage or change to the existing ecosystems. Details of this methodology and determination of the critical loads for eutrophication, acidificaiton and biodiversity can be found in Hettelingh et al., 2017 [47]. Critical loads are specified per country/region/area and per habitat type.

For a regenerative agriculture system we strive for a situation wherein the aerial losses (emissions) of nitrogen and sulphur from agricultural sources do not cause exceedance of the critical eutrophying and acidifying deposition loads for water bodies and soils, especially for EU disignated natural habitats. For water bodies this is covered by the Water Framework Directive, section 4. For EU designated nature areas eutrophying and acidifying effects negatively affect biodiversity, and required outcomes are given in section 9 Habitat for species. Due to the contribution of multiple sources to the deposition of especially nitrogen, and the transboundary transport through the air, intensive measurements and advanced modelling are needed to determine the contribution of spatially distributed agricultural sources to specific natural habitats, see e.g. [48].

7. Biological control and pollination

Healthy agricultural ecosystems provide functional agro-biodiversity. This enables regulation of pests and diseases through the presence of beneficial soil organisms that promote plant health, the activities of predators and parasites, as well as pollination of crops. For a regenerative agricultural ecosystem the following requirements need to be met[49]:

a. Presence of a resilient (above and below ground) food web with functional redundancy and sufficient density and diversity of important members of the food web. (system level: throughout each field)
b. Sufficient abundance and diversity of ‘natural predators on undesired species’ (system level: throughout each field)
c. Presence of resilient populations of pollinators i.e. with sufficient diversity and abundance.[50] (system level: local agriculture + nature)

[47] Hettelingh J-P, Posch M, Slootweg J (eds.) (2017) European critical loads: database, biodiversity and ecosystems at risk, CCE Final Report 2017, Coordination Centre for Effects, RIVM Report 2017-0155, Bilthoven, Netherlands.
[48] EMEP, 2017b, Transboundary particulate matter, photooxidants, acidifying and eutrophying components, EMEP Status Report 1/2017, European Monitoring and Evaluation Programme, Norway (http://emep.int/publ/reports/2017/EMEP_Status_Report_1_2017.pdf) accessed 8 July 2018.
[49] Quantification of these targets will follow later in the program
[50] See also Burkle, Delpha and O’Neil, 2017: A dual role for farmlands: food security and pollinator conservation,https://besjournals.onlinelibrary.wiley.com/doi/pdf/10.1111/1365-2745.12784

8. **Genetic diversity**

Genetic resources of plants, animals and micro organisms, including natural and forest genetic resources, lie at the basis of our food, fibre, shelter, timber, herbal medicines and draught animals. The ancient process of adapting plants and animals to human preferences and practices is called domestication and first started 10,000 years ago in areas where resources for food were diverse and abundant[51]. Local and national diversity also represents a cultural heritage. Natural as well as agricultural ecosystems need sufficient genetic diversity to ensure stability in ecosystem functioning and long term resilience to shocks. This requires diversity of species, sufficient abundance (size of populations) and genetic diversity within populations. Genetic diversity in the Netherlands is low indicated by the fact that the mean species abundance (MSA) is approximately15% of the original (pre-industrial revolution) situation. which is significantly lower than the european average MSA of approximately 40%[52]. Two international agreements provide a framework for efforts to conserve genetic resources and to promote their use: the 1992 Convention on Biological Diversity (CBD [53]) and the 2001 International Treaty on Plant Genetic Resources for Food and Agriculture [54]. We propose the following requirements on genetic diversity[55] :

a. Restore biodiversity to levels required for resilient natural ecosystems (system level: Netherlands, agriculture and nature combined);
b. Reversing the decline in abundance and diversity of farmland species for each specific type of agri/farmland use. (system level: local and regional, agriculture and nature combined);
c. Maintain (native) breeds and crops, and conserve genetic diversity within farm crop and animal species, complementary in situ and ex situ conservation approaches (in side and outside farms, fields and nature, respectively) (system level: Dutch agriculture and international).

9. **Habitats for species**

Habitats provide everything that populations of each specie need to survive: food; water; and shelter. Each ecosystem, including agricultural ecosystems, provides different habitats that can be essential for a species' lifecycle. Migratory species including birds, fish, mammals and insects all depend upon different ecosystems during their movements. To reverse the decline of biodiversity in the Netherlands (see requirement 8a.) and to enable biological control and pollination (requirement 7), the following required conditions for habitats need to be met:

a. Sufficient amount of natural habitats of sufficient size, and sufficient connectivity between natural habitats to allow for exchange of genetic material between populations of wild species, and for migration of species through the landscape. This requires that all natural habitats are located at distances that allow for direct migration of individuals through the landscape, or via corridors or stepping stones (system level: landscape). These distances strongly depend on the mobility of the species of interest and their home ranges, as well as the spatial configuration of the landscape, which includes non-agricultural land use. As a general threshold value for connectivity we propose as required condition that on *every* square kilometer more than 10% of the area consists of (semi-)natural habitats (system level: landscape including all land use types). This guideline should be targeted to

[51] CGN, 2020. Centre for Genetic Resources, Wageningen, brochure. https://edepot.wur.nl/180422
[52] See: https://themasites.pbl.nl/balansvandeleefomgeving/jaargang-2014/natuur/biodiversiteit-en-oorzaken-van-verlies-in-europa and https://www.pbl.nl/sites/default/files/downloads/pbl-2020-balans-van-de-leefomgeving-2020-4165.pdf.
[53] https://www.cbd.int
[54] http://www.fao.org/plant-treaty/en/
[55] Quantification of these targets will follow later in the program

landscape type and the characteristics of the species groups that are of local relevance.Hence the >10% requirement is a minimum threshold that may be higher depending on specific geographical location and the species concerned.[56] An overall index that could be used to set required conditions at local level is the Landscape Cohesion index, which uses ecological profiles of sets of indicator species and spatial information about connectivity of habitat in the landscape to provide a general cohesion index[57] (Opdam et al. 2003).

b. year round habitat and resource provision for farmland species for all stages of the life cycle (e.g. forage, nesting and overwintering habitat (system level: landscape). What exactly is required is highly location and species specific, so targets should be formulated based on local context

c. Adjacent agricultural landuse has neutral or positive impact on the conditions and resource availability in adjacent (semi-)natural habitat[58]:
   i. The eutrophying and acidifying effects of nitrogen and phosporus deposition on the biodiversity and habitats for species in EU designated nature areas is below the critical deposition level. This critical deposition level is dependent on the specific type of ecosystem of concern (Bobbink et al. 2010). Agriculture contributes its share to reach this goal. (system level: local agriculture + nature)
   ii. Water management in agricultural ecosystems have a neutral or positive impact on water availability in Natura 2000 area's and for local communities. (system level: local agriculture+nature) (see also requirement 4g)
   iii. No short nor long term threatening impact[59] on humans, natural ecosystems and functional agro-biodiversity from use of fungicides, nematocides, insecticides, herbicides and antibiotics and combinations thereof (system level: local agriculture + nature).

The requirements described so far are all biophysical requirements, that need to be achieved for sufficient food production and a positive impact on biosphere integrity. Next to achieving these biophysical requirements, a regenerative agriculture system at scale needs to contribute positively to human/animal well-being and economic prosperity of farmers and society. We propose the following five required socio-economic outcomes[60]:

10. **Farmer income**

Farmers need a financial compensation for their labour (and of co-workers), their investments in capital (land, machines, buildings) and for financial risks. This is generally expressed as a farm income, that should exceed a standard living income (system level: each farm). More specifically we propose the following required outcomes:

a. Free cash flow per farm exceeds a living income per hour of work (system level: each farm)

b. Short term price and yield risks are mitigated and do not threaten farmers' living incomes and long term economic healthiness of the farm.

c. Financial value added per farm sufficiently exceeds (potential) cost of capital per farm to enable transition of ownership to next generations

[56] Cormont et al. 2016
[57] Opdam et al. 2003; Landscape cohesion an index for the conservation potential of landscapes for biodiversity
[58] Smart et al. 2006
[59] Quantification of this target is not possible (yet). We aim to quantify later in the project
[60] These requirements cannot all be quantified (yet). Where possible they will be quantified later in the project

11. **Animal welfare and health**
Animal welfare and animal health are important aspects of livestock farming, not only for the animals themselves, but also for the farmer, the local ecological system, consumers and society at large. In a Regenerative Agriculture farm animals have a life worth living. The farming systems should thereof comply to the 5 freedoms of animal welfare [61], which are more detailed in the physiological and behavioural needs of animals [62]. This means, amongst others, that animals can express species specific behaviours and have freedom of choice. The EU Welfare Quality protocol can be used to asses animal welfare and health at herd or farm level [63]. Instead, we choose to define the following conditions for animals kept for livestock production.
   a. Besides fulfilling the production related conditons of e.g. feed and water quantity and quality, sufficient space per animal and crucial facilities must be present and accessible by the animals. For laying hens this means at least 2200 cm^2 per hen and presence of a perch and foraging and dustbahing material. For e.g. fattening pigs (at weight of 100 kg) this means 2 m^2 per animal and presence of rooting material and separted defecating/urination areas;
   b. Animals can meet all these needs without pain and injuries. Interventions that violate the integrity of the animal, like dehorning of cows, tail docking of pigs, beaktrimming of hens, are not executed. Injuries resulting from environmental conditons are absent, like foot pad lesions with broilers, lameness and skin injuries for cows, and damaged feather plumage for laying hens.
   c. Limitations incurred by genetic selection and management practices to normal behaviour are absent. This specifically refers to feed restrictions that are applied in case of reproducing parent stock to avoid excessive overweight, and typically applied in case of parent stock of broilers and pigs.

   Details of this approach and underpinning can be found in Bos et al. 2017) [64].

12. **Quality of employment (work / labour)**
The regenerative agriculture sector provides attractive and meaningful work according to seven dimensions of quality of employment as defined by the United Nations Economic Commission for Europe (UNECE) in a structured and coherent system for measuring quality of employment (system level: each farm) [65]. The statistical framework defines quality of employment from the point of view of the employed person; not from the societal or corporate view. Detailed descriptions of each indicator – indicator sheets – have been developed to provide guidance for the computation and interpretation of the indicators:
   a. safety & ethics of employment,
   b. income & benefits from employment,
   c. working time & work/-life balance,
   d. security of employment & social protection,
   e. social dialogue,
   f. skills development & training
   g. employment-related relationships & work motivation.

[61] Brambell, 1965/1967. UK Farm Animal Welfare Advisory Committee
[62] Bracke, M.B.M., B.M. Spruit, J.H.M. Metz, 1999. Overall animal welfare reviewed. Part 3: welfare assessment based on needs and supported by expert opinion. NJAS 47 (3/4): 307-322
[63] http://www.welfarequality.net/en-us/reports/assessment-protocols/
[64] Bos, A.P. D. Puente-Rodríguez, J.W. Reijs, G.F.V. van der Peet and P.W.G. Groot Koerkamp, 2017. Monitoring verduurzaming veehouderij 1.0 - Een eerste proeve van een Monitorings-systematiek voor de 15 ambities van de Uitvoeringsagenda Duurzame Veehouderij, met initiële resultaten voor drie diersectoren en een aantal keteninitiatieven. Wageningen Livestock Research, report 1045.
[65] UNECE Expert Group on Measuring Quality of Employment. (2013). Draft statistical framework for measuring quality of employment. *Nineteenth International Conference of Labour Statisticians*, see Annex 4

13. Quality of landscapes

Agro-ecosystems in combination with nature provide for attractive landscapes and experiences for people who wish to visit them (system level: local agriculture + nature)

a. All 78 landscapes identified by the Netherlands Cultural Heritage Agency are maintained and any negative impact of the primary/ agricultural production sector on these landscapes is minimized. Desired landscape quality is determined by provincial governments, and landscape integrity serves as a condition for agricultural production[66].

14. Rural-urban connection

Citizens in rural and urban areas enjoy a good connection based on mutual respect, trust and appreciation. We defined the following required outcomes (system level: the Netherlands):

a. All primary agricultural sectors score at least a 6 out of 7 in the biennial Agrifoodmonitor survey[67];
b. More than 90% of farmers feel their work is valued by society[68];
c. The density of hospitality businesses as well as cultural, sports and recreational establishments in Dutch rural areas is at or above the current Dutch average of 10 per 1,000 inhabitants[69].

Summary

Table 3 provides a summary of the required outcomes that we propose. The upper half of this table summarizes the required outcomes at field and farm level. To get to a regenerative system every farm needs to meet these required outcomes over time. The lower half of table 3 summarizes the required outcomes at higher system levels (local landscape, the Netherlands or international). These are requirements that cannot all be met by individual farms. For a regenerative system at scale there will be a need to create symbiotic mixes of a diversity of farm systems, as well asnature, that combined generate a net outcome that meets all the requirements at the appropriate scales.

[66] College van Rijksadviseurs. (2018). *Panorama Nederland*.
[67] https://edepot.wur.nl/466021
[68] https://destaatvandeboer.trouw.nl/resultaten/
[69] https://www.cbs.nl/nl-nl/nieuws/2018/23/wadden-hebben-meeste-winkels-en-horeca-per-inwoner; for rationale see Callois, J. M., & Aubert, F. (2007). Towards indicators of social capital for regional development issues: The case of french rural areas. *Regional Studies*, *41*(6), 809–821. https://doi.org/10.1080/00343400601142720

Table 3: Summary of required outcomes for a regenerative agriculture system at scale

Ecosystem services/ soil functions	Required outcomes at field and/or farm level	Field	Farm
1. Soil quality + fertility, 3. carbon & climate regulation	• A resilient soil food web with functional redundancy; high abundance and richness of soil micro-biome • Resilient soil physical quality; a.o. dry bulk density < 1.6 g/cm^{-3} of dry matter • Soil organic matter > 4%-8% (soil and farm type dependent)	■	
4. Water purification & regulation	• Water usage ≤ natural available • Water storage capacity > … (soil type dependent)		■
5. Provision & cycling of nutrients	• N and P accumulation in soils limited to levels that minimize the risk of leaching and high emissions to the environment • All N, P and micro-nutrients inputs in system come from renewable sources (air, manure or recovered from sewage/environment)	■	
6. Local air quality	• No accumulation of Persistent organic pollutants (POPs) in soils, water or air	■	
7. Biological control & pollination 8. Genetic diversity, 9. Habitats for species	• >10% of each square km landscape (public space + farmland combined) is semi natural habitat • year-round diversity of habitat and resource provision for farmland species for all stages of the life cycle. (providing habitat for farmland species and enabling natural pest control) • Abundance and diversity of populations for natural pest control	■	■
10. Farmer income, 11. animal welfare, 12. attractive work	• Farmer incomes ≥ living income • Farm animals have a life worth living • Farms provide attractive and meaningful work		■

Ecosystem services/ soil functions	Required outcomes at local or higher level	Local Land scape	NL	Europe/ global
1. Soil quality + fertility, 3. carbon & climate regulation	• Agriculture and nature combined are a 'net carbon sink' • In between step, deliver on commitments in climate agreement, i.e. reduce net GHG-emissions from Dutch Agri + landuse with > 6 MT by 2030		■	■
2. Primary productivity of food & nutrition, raw materials and medicinal resources	• Average production/ha high enough to produce sufficiënt food and biomass on < 11-15 M KM^2 cropland, globally • Circular system; input output ratio of human digestible protein < 1	■	■	■
4. Water purification & regulation	• Water quality good/very good according to water framework directive • Water surpluses are collected as buffer • No negative impacts on water in natural areas and for local communities	■		
5. Provision and cycling of Nutrients, 6. Local air quality	• Particulate matter < WHO limits • N deposition in natural habitats < EU limits • NO and NO_2 emissions within EU directives	■		
7. Biological control & pollination 8. Genetic diversity, 9. Habitats for species	• >10% of each square km landscape (public space + farmland combined) is semi natural habitat • Migration of species between all nature areas enabled • Abundance and diversity of farm-land species and pollinators • Diversity of gene pool for locally well-adapted crops and farm animals	■	■	
13. attractive landscapes, 14. connection rural/urban	• Agricultural ecosystems in combination with nature provide attractive landscapes • Good connection between rural and urban communities		■	

6 Next steps with this outline in the regenerative agriculture project

In the next phase of the regenerative agriculture project, this outline will be used to assess the potential impact of existing best practices and to design future scenario's in compliance with the outline.

For this design of scenario's that meet all the required outcomes at the relevant system levels, we expect the need for a mosaic of innovative solutions. Some of these solutions may exist as best practices today, but most likely there will be a need to design 'next practice' solutions.

In **work package 2** we have identified a number of best agricultural practices that may contribute to a regenerative system. These practices vary from system approaches in order to create a new system, to relatively small adjustmens to the current system. This list is work in progres. Many farmers also make combinations of various practices The list so far consists of the following practices:

Ground-bound plant production practices:
- High diversity cropping patterns and cover crops/ 'stroken teelt': (example: Erf, 'the future farm')
- No/minimize tillage (example: Huiberts bloembollen)
- Soil innoculation (example: Nature restoration projects)
- Use perennials (example: Luzerne)
- Use of green manures, compost, crop residues (examples: Klompe, VICOE)
- High tech precision arable farming (example: van den Borne)
- Tree intercropping (trees & arable farming) (example: Proefboerderij Lelystad)
- Permacultures/Agroforestry (examples: Us Hof)
- Food forests (example: Ketelbroek)
- Riparian buffers (example:…….)
- Conservation (wild harvesting)

Ground-bound animal production practices:
- Managed (strip) grazing on permanent herb rich grasslands (example: Graasboerderij)
- Silvo pastures (trees & permanent grasslands) (example: graasboerderij)
- Minimized losses conventional animal husbandry (example: Vruchtbare kringlopen achterhoek)

Ground-bound mixed plant/animal production practices:
- Integrated farm, in a new local ecosystem (example: Herenboeren)
- Local/Regional x-sector cooperation (example Ecolana)

Non ground-bound circular systems:
- Intensive circular animal husbandry (example: Kipster)
- High tech circular horticulture/urban vertical LED farming (example:…..)
- High tech circular mixed farming (example: Saimniecibas Kopskats [latvia], Geofood Bleiswijk)

In **work package 4.1** we will analyze the sustainability gap between these best practices and a regenerative system at scale. We will do so by analysing how each of these practices perform versus the required outcomes that are described in chapter 4, and by subsequently modelling the best possible mix(es) of today's best practices.

In **work package 4.2** we will subsequently design and model future scenario's, i.e. symbiotic mix(es) of next practices, that can fully meet the required outcomes. We will do so by first designing regenerative systems at landscape level for different soil types (sand, peat, clay) in 2020. In 2021 this will be followed by more detailed next-practice design of specific production systems:

- a ground-bound plant production system,
- a ground-bound animal protein production system,
- a ground-bound mixed system and
- a non ground-bound circular system)

Future scenario's that meet all the requirements of this document will only be feasible if the proposed solutions in these scenario's will have sound business models. Therefor, in **work package 3**, we will work with innovative farmers and with research facilities like 'the future farm' to explore regenerative business models and new models to organize regenerative practices at scale. We foresee that regenerative business models have to differ from conventional agri commodity business models, in order to be competitive. In the best practices, we identified a number of options for differentiated business models that we will explore further in WP 3:

- Differentiated product (taste, nutrition, local heritage, organic and other sustainability labels) resulting in price premium
- Lower input costs (animal feed, herbicides, pesticides, chemical fertilizer,…)
- Less asset intensive, and less specialized assets
- Different ownership of assets (e.g. consumers owning a local farm)
- Multi-product synergies (yields and/or costs)
- Revenues from ecosystem services, most notably:
    - Carbon sequestration
    - Water retention, percolation and purification
    - Crop and biological diversity and nature conservation
    - Cultural ecosystem services
- Short value chains of local production for the direct need of local consumers
- Forward intergration into local processing of a premium branded local product
- As a result of the above: lower risks and better financing conditions (interest rates and pay back periods)

This exploration will lead to a usable handbook for new business models for regenerative agriculture.

Finally, in **work package 5** we will build on the findings of work packages 3 and 4, analyze the so-called 'think do' gap and elaborate transition scenario's and interventions in the socio-economic system to overcome this gap.

Annex 1: Source frameworks for defining required outcomes

1.1 Ecosystem services according to 'The Economics of Ecosystems and Biodiversity' (TEEB):

Provisioning services:

- **Food**: Ecosystems provide the conditions for growing food. Food comes principally from managed agro-ecosystems but marine and freshwater systems or forests also provide food for human consumption. Wild foods from forests are often underestimated.
- **Raw materials**: Ecosystems provide a great diversity of materials for construction and fuel including wood, biofuels and plant oils that are directly derived from wild and cultivated plant species.
- **Fresh water**: Ecosystems play a vital role in the global hydrological cycle, as they regulate the flow and purification of water. Vegetation and forests influence the quantity of water available locally.
- **Medicinal resources**: Ecosystems and biodiversity provide many plants used as traditional medicines as well as providing the raw materials for the pharmaceutical industry. All ecosystems are a potential source of medicinal resources

Regulating services:

- **Local climate and air quality**: Trees provide shade whilst forests influence rainfall and water availability both locally and regionally. Trees or other plants also play an important role in regulating air quality by removing pollutants from the atmosphere.
- **Carbon sequestration and storage**: Ecosystems regulate the global climate by storing and sequestering greenhouse gases. As trees and plants grow, they remove carbon dioxide from the atmosphere and effectively lock it away in their tissues. In this way forest ecosystems are carbon stores. Biodiversity also plays an important role by improving the capacity of ecosystems to adapt to the effects of climate change.
- **Moderation of extreme events**: Extreme weather events or natural hazards include floods, storms, tsunamis, avalanches and landslides. Ecosystems and living organisms create buffers against natural disasters, thereby preventing possible damage. For example, wetlands can soak up flood water whilst trees can stabilize slopes. Coral reefs and mangroves help protect coastlines from storm damage.
- **Waste-water treatment**: Ecosystems such as wetlands filter both human and animal waste and act as a natural buffer to the surrounding environment. Through the biological activity of microorganisms in the soil, most waste is broken down. Thereby pathogens (disease causing microbes) are eliminated, and the level of nutrients and pollution is reduced.
- **Erosion prevention and maintenance of soil fertility**: Soil erosion is a key factor in the process of land degradation and desertification. Vegetation cover provides a vital regulating service by preventing soil erosion. Soil fertility is essential for plant growth and agriculture and well functioning ecosystems supply the soil with nutrients required to support plant growth.
- **Pollination**: Insects and wind pollinate plants and trees which is essential for the development of fruits, vegetables and seeds. Animal pollination is an ecosystem service mainly provided by insects but also by some birds and bats. Some 87 out of the 115 leading global food crops depend upon animal pollination including important cash crops such as cocoa and coffee (Klein et al. 2007).
- **Biological control**: Ecosystems are important for regulating pests and vector borne diseases that attack plants, animals and people. Ecosystems regulate pests and diseases through the activities of predators and parasites. Birds, bats, flies, wasps, frogs and fungi all act as natural controls.

Habitat & supporting services:

- **Habitats for species**: Habitats provide everything that an individual plant or animal needs to survive: food; water; and shelter. Each ecosystem provides different habitats that can be essential for a species' lifecycle. Migratory species including birds, fish, mammals and insects all depend upon different ecosystems during their movements.
- **Maintenance of genetic diversity**: Genetic diversity is the variety of genes between and within species populations. Genetic diversity distinguishes different breeds or races from each other thus providing the basis for locally well-adapted cultivars and a gene pool for further developing commercial crops and livestock. Some habitats have an exceptionally high number of species which makes them more genetically diverse than others and are known as 'biodiversity hotspots'.

Cultural services:

- **Recreation and mental and physical health**: Walking and playing sports in green space is not only a good form of physical exercise but also lets people relax. The role that green space plays in maintaining mental and physical health is increasingly being recognized, despite difficulties of measurement.
- **Tourism**: Ecosystems and biodiversity play an important role for many kinds of tourism which in turn provides considerable economic benefits and is a vital source of income for many countries. In 2008 global earnings from tourism summed up to US$ 944 billion. Cultural and eco-tourism can also educate people about the importance of biological diversity.
- **Aesthetic appreciation and inspiration for culture, art and design**: Language, knowledge and the natural environment have been intimately related throughout human history. Biodiversity, ecosystems and natural landscapes have been the source of inspiration for much of our art, culture and increasingly for science.
- **Spiritual experience and sense of place**: In many parts of the world natural features such as specific forests, caves or mountains are considered sacred or have a religious meaning. Nature is a common element of all major religions and traditional knowledge, and associated customs are important for creating a sense of belonging.

1.2 Functional Land Management - the concept of soil functions

Functional Land Management is a conceptual science-based framework for optimizing the supply of soil-based ecosystem services. These soil-based ecosystem services are grouped together in five overarching soil functions, to the demands at a range of spatial scales, with a view to simultaneously meeting agronomic and environmental policy objectives. The five overarching soil functions are described by Schulte et al. (2014) as:

1. **Primary productivity**:
   the capacity of a soil to produce plant biomass for human use, providing food, feed, fiber and fuel within natural or managed ecosystem boundaries.
2. **Water purification and regulation:**
   the capacity of a soil to remove harmful compounds from the water that it holds and to receive, store and conduct water for subsequent use and the prevention of both prolonged droughts and flooding and erosion.
3. **Carbon sequestration and regulation**:
   the capacity of a soil to reduce the negative impact of increased greenhouse gas (i.e., CO2, CH4, and N2O) emissions on climate.
4. **Provision of functional and intrinsic biodiversity:**
   the multitude of soil organisms and processes, interacting in an ecosystem, making up a significant part of the soil's natural capital, providing society with a wide range of cultural services and unknown services.
5. **Provision and cycling of nutrients**:
   the capacity of a soil to receive nutrients in the form of by-products, to provide nutrients from intrinsic resources or to support the acquisition of nutrients from air or water, and to effectively carry over these nutrients into harvested crops.

These soil functions are performed by every soil simultaneously, however, the extent and the relative composition of this functionality depends upon pedological, physical, chemical and biological soil properties. Each soil function has a definition and it is described by a set of attributes, visually represented by a DEXi tree. Attributes are soil properties which can be measured, the DEXi trees show the relationship between the attributes and show the formation of aggregated indicators which lead to the specific soil function.

Soil quality is the extent to which a soil can perform its soil functions. A soil with 'high soil quality' can deliver the desired functions to meet demands, whereas a soil with 'low soil quality' delivers functions at sub-optimal rates. Soil functions refer to soil based ecosystem services, which is one elemental aspect of the soil system that contributes to the generation of goods and services.

For more information: http://landmark2020.eu/soil-functions-concept/

1.3 Planetary boundary targets from EAT-Lancet

In the EAT-Lancet report (2019) a number of targets are set for the global food system to operate within planetary boundaries (see figure 5).

Earth system process	Control variable	Boundary (Uncertainty range)
Climate change	GHG emissions	5 Gt CO_2-eq yr^{-1} (4.7 – 5.4 Gt CO2-eq yr^{-1})
Land-system change	Cropland use	13 M km^2 (11–15 M km^2)
Freshwater use	Water use	2,500 km^3 yr^{-1} (1000–4000 km^3 yr^{-1})
Nitrogen cycling	N application	90 Tg N yr^{-1} (65–90 Tg N yr^{-1}) * (90–130 Tg N yr^{-1})**
Phosphorus cycling	P application	8 Tg P yr^{-1} (6–12 Tg P yr^{-1}) * (8–16 Tg P yr^{-1})**
Biodiversity loss	Extinction rate	10 E/MSY (1–80 E/MSY)

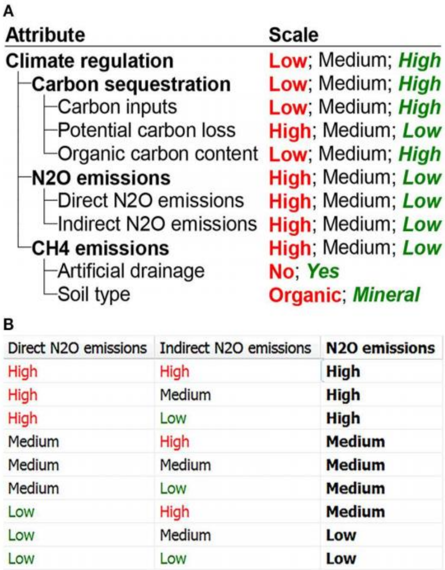
Figure 5: Targets for global food system to operate within planetary boundaries according to EAT-Lancet

Annex 2: Description of The Soil Navigator DSS (decision support system)

The Functional Land Management framework (see annex 1.2) was further articulated in a decision support tool (DSS) named the Soil Navigator DSS (Debeljak et al., 2019[70]). The Soil Navigator DSS supports farmers and farm advisors to assess and optimize the five soil functions. The Soil Navigator DSS is evidence-based and targeted for assessing and improving the supply of several soil functions simultaneously for long-term sustainability. The Soil Navigator DSS provides a menu of user-friendly soil management strategies to manage the soil functions on individual fields on the farm (local scale). The menu is stratified by pedo-climatic zones, land uses (cropland and grassland) and farming systems. The Soil Navigator currently grades soil functions on a 3 point scale: low, medium and high. . The overall aim is that farmers score at least medium on all soil functions and score highfor two three of the soil functions. At landscape level the overall aim is that the delivery of all soil functions is optimised to ensure that both functional and societal demands are met.

In the designing of the Soil Navigator DSS qualitative multi-criteria decision analysis has been applied using Decision EXpert (DEX) integrative modelling methodology. Five teams of scientific experts have structured, calibrated and validated DEX models for the five soil functions: primary productivity, water purification and regulation, carbon sequestration and climate regulation, nutrient cycling and biodiversity and habitat provision. Subsequently, the DEX models have been integrated into the Soil Navigator DSS to permit the assessment of these soil functions simultaneously, and to provide management recommendations for improving the supply of prioritized soil functions.

Moreover the construction of the Soil Navigator DSS is described in Debeljak et al. (2019). First, input data for the DSS comes from the end-users that provides specific attributes about their field and the applied management practices. Another part of the data is collected from existing databases (soil, meteorological databases) to which the system is internally connected. Secondly, input data is transformed to a format suitable for feeding all models. Thirdly, The decision models help the decision makers to rank a set of best decision alternatives relevant for the soil functions. Since the model deals with a multi-criteria decision problem, they used multi-criteria decision models (MCDM) for the analysis of their decision problem. Their approach is based on the application of analytical hierarchical processes, in which complex decision problem are decomposed into less complex subproblems represented by attributes structured into a hierarchy linked by integrative functions (See Figure 6). The model, therefore, consists of basic attributes (input data), aggregated attributes (internal nodes), which provide the assessment of the alternatives at various hierarchical levels, and the root attribute (top attribute), which gives



A

Attribute	Scale
Climate regulation	Low; Medium; ***High***
Carbon sequestration	Low; Medium; ***High***
Carbon inputs	Low; Medium; ***High***
Potential carbon loss	High; Medium; ***Low***
Organic carbon content	Low; Medium; ***High***
N2O emissions	High; Medium; ***Low***
Direct N2O emissions	High; Medium; ***Low***
Indirect N2O emissions	High; Medium; ***Low***
CH4 emissions	High; Medium; ***Low***
Artificial drainage	No; ***Yes***
Soil type	Organic; ***Mineral***

B

Direct N2O emissions	Indirect N2O emissions	**N2O emissions**
High	High	**High**
High	Medium	**High**
High	Low	**High**
Medium	High	**Medium**
Medium	Medium	**Medium**
Medium	Low	**Medium**
Low	High	**Medium**
Low	Medium	**Low**
Low	Low	**Low**

Figure 6. Top part of the DEX model for the climate regulation and carbon sequestration soil function. (A) Hierarchical structure and scale values of attributes. (B) Integration rules for integration of direct and indirect N_2O emissions into N_2O emissions.

[70] Debeljak M, Trajanov A, Kuzmanovski V, Schröder J, Sandén T, Spiegel H, Wall DP, Van de Broek M, Rutgers M, Bampa F, Creamer RE and Henriksen CB (2019) A Field-Scale Decision Support System for Assessment and Management of Soil Functions. Front. Environ. Sci. 7:115. doi: 10.3389 / fenvs.2019.00115

the overall assessment of the alternatives and presents the final output of the model. At each aggregation in the hierarchy a decision table made by best expert knowledge assigns a finite set of qualitative (nominal) values (e.g., low, medium, high; suitable, not suitable; wet, dry) to each attributes in the model.

During and after the creation of the models verification was performed in order to test their internal operational logic and behavior. The verification was performed by domain experts and end-users (farm advisors and farmers) who used both theoretical case study scenarios as real-world data. When the verification of all soil function decision models was completed, a sensitivity analyses was carried out to find input attributes whose values had a negligible impact on the model behavior. These attributes were removed from the models to reduce the model complexity.

Attributes / indicators in the DEX models (Debeljak et al., 2019)

An overview of the structural properties of the DEX models which include the number of attributes used on different hierarchical levels is presented in Table 4 (Debeljak et al., 2019). The primary attributes of each of the soil functions will be discussed accordingly.

Table 4. Structural properties of the DEX models of all soil functions.

Soil function models	Total number of attributes	Number of aggregated attributes	Number of input attributes	Number of hierarchical levels	Number of integration rules
Primary productivity	42	16	25	4	294
Nutrient cycling	51	27	24	5	302
Climate regulation	540	21	19	5	301
Water regulation and purification	116	77	39	6	800
Biodiversity and habitat	55	24	31	5	612

The **primary productivity** decision model consists of sub-models describing the environmental conditions, inherent soil conditions (physical: structure, groundwater table depth; chemical: micro- and macro-elements; biological: pH, C/N ratio, soil organic matter), soil management, and crop properties. Primary productivity, as the top attribute, integrates the sub-models, which leads to an assessment of the capacity of a soil to produce biomass. A detailed description of the primary productivity model is given in Sandén et al. (2019).

The **nutrient cycling** decision model consists of three sub-models, integrated into the top attribute, describing the ability of a soil to provide and cycle nutrients. The first sub-model comprises nutrient fertilizer replacement value, which describes the extent to which nutrients, particularly those in left or applied organic residues, are as available to plants as manufactured mineral fertilizers. The second part of the model describes the extent to which plant-available nutrients are effectively taken up by crops and the last part addresses the harvest index describing the extent to which the nutrients taken up by crops are eventually leaving the field in the form of successful harvests (Schröder et al., 2018).

The **climate regulation and carbon sequestration** decision model integrates carbon sequestration, N_2O emissions and CH_4 emissions. The carbon sequestration sub-model is determined by the magnitude of carbon inputs, carbon losses, and the soil organic carbon concentration. The N_2O emissions sub-model makes a distinction between direct N_2O emissions occurring on agricultural fields, and indirect N_2O emissions, after reactive N species have been transported through the landscape. The part of the model addressing CH_4 emissions are determined by the extent to which artificial drainage is applied on organic soils. Detailed information about the model are given in Van de Broek et al. (unpublished to date).

The **water regulation and purification** decision model integrates three sub-models describing the prevailing soil water pathways: water storage, water runoff, and water percolation. Water storage is determined by the attributes used for assessing the water holding capacity and soil moisture deficit. Water runoff is determined by the attributes used for assessing the water-, sediment-, and nutrient-related runoff. The water percolation sub-model is determined by the attributes used for assessing the resulting drainage of excess of water above that potentially stored in the soil and the resulting nutrient leaching and losses (Wall et al., 2018)

The **soil biodiversity and habitat provisioning** decision model integrates four sub-models describing soil nutrients (status, trends, turnover, and nutrients availability), soil biology (available information on diversity, biomass, and activity of soil organisms), soil structure [structure and density, ranging from mesoscale (coarse fractions, soil particles, organic matter, air, and water-filled space) to macroscale (soil layers, terrain, slope)], and soil hydrology (soil humidity and the soil water flow pathways) (Rutgers et al., 2019).

For more information: http://landmark2020.eu/pillars/soil-navigator-pillar1/

Annex 3: Existing certification and outcome measurement frameworks related to regenerative agriculture

To our knowledge, two regenerative agricultural based certification frameworks are currently being developed (Ecological Outcome Verification and Regenerative Organic Certification). Though operational, these frameworks are not widely acknowledged yet. However, they are supported by academic actors. The frameworks will be briefly discussed below, as well as a minimal set of indicators for Dutch soils.

1. Ecological Outcome Verification[71]

The Ecological Outcome Verification (EOV) of the Savory Institute is a framework which is based on the Ecological Health Index, for short and long term assessment of ecological health (Xu et al., 2019). It is an outcome based framework taking explicitly ecological health of grazing land into account. The framework uses 15 indicators to assess ecological health (Table 5). These indicators are assessed on criteria e.g. perennial vegetation cover exceeds 60%, bare ground less than 20%.

Table 5. The list of 15 indicators for ecological health from the Ecological Health Index, with their unit, indicator type and link with water and mineral cycle, energy flow and community dynamics (indicated with green box?).

#	Indicator	Unit	Type	Water Cycle	Mineral Cycle	Energy Flow	Community Dynamics
1	Live Canopy Abundance	Total green biomass production/Site potential	Ref. Area				
2	Living Organisms	Evidence of microfauna	Absolute				
3	FG1 – Warm Season Grasses	Vigor, reproduction, crown integrity	Absolute				
4	FG2 – Cool Season Grassess	Vigor, reproduction, crown integrity	Absolute				
5	FG 3 – Forbes/Legumes	Vigor, reproduction, crown integrity	Absoute				
6	FG 4- Desirable Trees/shrubs	Vigor, reproduction, crown integrity	Absolute				
7	Contextually Desirable Rare Species	Frequency	Ref. Area				
8	Contextually Undesirable Species	Abundance	Ref. Area				
9	Litter Abundance	% Cover	Ref. Area				
10	Litter Incorporation	Litter type, Soil contact	Absolute				
11	Dung Decomposition	Dung Disappearance rate	Absolute				
12	Bare Soil	% Bare Soil	Ref. Area				
13	Capping	Soil surface resistance	Absolute				
14	Wind Erosion	Blowout/Deposition; Active pedestals	Absolute				
15	Water erosion	Rills/water flows; Gullies	Absolute				

2. Regenerative Organic Certification

The Regenerative Organic Certification (ROC) of the Regenerative Organic Alliance (ROA) is represented by various actors such as the Rodale Institute. They present guidelines for the food production value chain as a list of suggested practices. The guidelines use USDA Organic certification as a baseline requirement and ad requirements in their three pillars of soil health and land management, animal welfare, and farmer and worker fairness. Their three goals are: 1) to increase soil organic matter over time and sequester carbon below and above ground, which could be a tool to mitigate climate change, 2) to improve animal welfare, and 3) to provide economic stability and fairness for farmers, ranchers, and workers

[71] Xu, S.; Rowntree, J.; Borrelli, P.; Hodbod, J.; Raven, M.R. Ecological Health Index: A Short Term Monitoring Method for Land Managers to Assess Grazing Lands Ecological Health. Environments 2019, 6, 67.

(Table 6). Aspects which are taken into account in this framework are besides ecological health also land management issues, social, and economic aspects.

Table 6. Aspects taken into account in Regenerative Organic Certification (ROC) of the Regenerative Organic Alliance (ROA).

#	**Soil Health and Land management**	**Animal welfare**	**Farmers and Working Fairness**
1	Agroforestry	Body condition score	Capacity Building
2	Biodiversity	Carying capacity	Democratic Organizations
3	Carbon sequestration	Concentrated Animal Feeding Operations	Equal Opportunity
4	Compost	Commercial Livestock Operations	Fair Payments
5	Cover cropping	Five Freedoms	Freedom of Association and Collective Bargaining
6	Crop rotation	Handling	Living Wage
7	Invasive species	Mobile Harvesting Unit	Routine Workplace Audits
8	Pasture	Monogastric	Smallholder
9	Perennial crops	Non-Ambulatory Animals	Trafficked Labor
10	Riparian areas	Ruminants	
11	Rotational grazing		
12	Silvopasture		
13	Soil health		
14	Tillage		

3. Minimal dataset for soil quality assessment[72] [73] [74]

A report from Wageningen Research in assignment of the ministry of LNV created a minimal set of indicators (17), which are supposed to be unambiguously, robust and academically substantiated, and listed in Table 7. The report also presents (simple) measurement methods and reference values for Dutch soils (sand and clay) (Table 8). The indicators presented are combined from previous academic research of Van den Elsen et al. (2019) and De Haan et al. (2019).

[72] Hanegraaf, M.C., H.G.M. van den Elsen, J.J. de Haan & S.M. Visser (2019). Bbodemkwaliteitsbeoordeling van landbouwgronden in Nederland – indicatorset en systematiek, versie 1.0. Wageningen Research, Rapport WPR-795. 34 blz. ; 1 fig; 2 tab; 23 ref.
[73] Elsen, H.G.M. van den, M. Knotters, M. Heinen, P.F.A.M. Römkens, J. Bloem, & G.W. Korthals, 2019. Noodzakelijke indicatoren voor de beoordeling van de gezondheid van Nederlandse landbouwbodems; De meest relevante fysische, chemische en biologische indicatoren voor het meten van de bodemgezondheid. Rapport 2944, Wageningen Environmental Research. http://edepot.wur.nl/475874
[74] Haan, J.J. de, S. Rombouts. L. Molendijk, W. Sukkel, H. Hoek & T. Thoden. 2019. Meten is Weten Weten Wageningen University & Research – in press.

Table 7. Selected indicators to assess soil quality, combined from Van den Elsen et al., (2019) en De Haan et al.

	Nr	Indicator	Eenheid	Klassieke meetmethode	Snelle, goedkopere meetmethode[2]
Org Stof	1	Organische stofgehalte en koolstofgehalte	%	Gloeiverlies en Dumas	NIRS
Org Stof	2	Stabiele fractie organische stof	%	Oxidatie in permanganaat (POXC)	n.b.
Org Stof	3	Heet water extraheerbare koolstof (HWC)	mg kg^{-1}, g ha^{-1}	Extractie in heet water	n.b.
Fysisch	4	Watervasthoudend vermogen	%, mm	Zandbak/drukpan	o.b.v. textuur + OS
Fysisch	5	Aggregaatstabiliteit	-	Natte zeefmethode	n.b.
Fysisch	6	Textuur	%	Pipetmethode	NIRS
Fysisch	7	Indringingsweerstand	Mpa	Penetrometer	
Fysisch	8	Droge bulkdichtheid	kg m^{-3}	Massa na drogen 105° C	Berekend uit OS%
Chemisch	9	Zuurgraad (pH)	-	Extractie in $CaCl_2$	
Chemisch	10	N-totaal	g kg^{-1}, kg ha^{-1}	Kjeldahl	NIRS
Chemisch	11	Potentieel mineraliseerbare stikstof (PMN)	mg kg^{-1}, g ha^{-1}	Anaerobe incubatie	NIRS
Chemisch	12	Fosfaatstatus[3]	mg 100 g^{-1}, g kg^{-1}, kg ha^{-1} mg 100 ml^{-1}	Extractie in ammoniumlactaat-azijnzuur, $CaCl_2$ resp. water	
Chemisch	13	Kalistatus[3]	mg 100 g^{-1}, $mmol^{+}$/kg, g kg^{-1}, kg ha^{-1}	Extractie in HCl en oxaalzuur	NIRS + Extractie in $CaCl_2$
Biologisch	14	Aaltjes diversiteit en aantallen (incl. plantparasitaire aaltjes)	Aantal taxa # 100 ml^{-1} grond	Microscopie	PCR
Biologisch	15	Bacterie- en schimmelbiomassa	µg kg^{-1}	PLFA	NIRS
Biologisch	16	Regenwormen aantallen en diversiteit	# m^{-2}, kg m^{-2}	Visueel	n.b.
Alg	17	Visuele beoordeling (fysisch-chemisch-biologisch)	Divers	Visueel	n.b.

Table 8. Reference values for soil-landuse combinations of arable farming on clay and sandy soil; dairy farming on clay and sandy soil from Hanegraaf et al., (2019). N.b. means not available. For chemical indicators from the "Handboek Bodem en Bemesting" and the "Adviesbasis Grasland" and "Voedergewassen" are the reference values also target values.

	Nr	Indicator	Meetmethode	referentiewaarden				Bron
				Akkerbouw op klei	Akkerbouw op zand	Melkveehouderij op klei	Melkveehouderij op zand	
Org Stof	1	Organische stofgehalte (%)	Gloeiverlies	1.6 - 3.6	3.3 - 16.2	3.4 - 13.5	3.8 – 11.2	Rutgers et al., 2007
Org Stof		Koolstofgehalte (%)	Dumas	n.b.	n.b.	n.b.	n.b.	
Org Stof	2	Stabiele fractie organische stof	Oxidatie in permanganaat (POXC)	n.b.	n.b.	n.b.	n.b.	n.b.
Org Stof	3	Heet water extraheerbare koolstof (HWC, mg kg^{-1})	Extractie in heet water	500	500 – 2000	n.b.	700 – 2300	Hanegraaf et al., 2009; Hanegraaf en Van Alebeek, 2014
Fysisch	4	Watervasthoudend vermogen[1]	Zandbak/drukpan	0.24	0.19	0.24	0.19	Wosten et al., 2001, Heinen et al., 2019
Fysisch	5	Aggregaatstabiliteit[2]	Natte zeefmethode	n.b.	n.b.	n.b.	n.b.	Nimmo et al., 2002 Eijkelkamp 2018
Fysisch	6	Textuur[3]	Pipetmethode					NEN 5753 en/of ISO 11277
Fysisch	7	Indringings-weerstand[4] (MPa)	Penetrometer	< 2 à 3	< 2 à 3	< 2 à 3	< 2 à 3	Handboek Bodem en Bemesting
Fysisch	8	Droge bulkdichtheid[5] (kg m^{3})	Massa na drogen 105° C	< 1.75-0.009*lutum - < 1.6 - < 1.75-0.009*lutum - < 1.6				NEN-EN-ISO 11272:2017
Chemisch	9	Zuurgraad (pH)[6]	Extractie in $CaCl_2$	7.3 - 7.7	4.6 - 5.6	5.2 - 7.4	4.7 - 5.8	Rutgers et al., 2007
Chemisch				> 6.7	n.b.	n.b.	5.0 - 5.7	Eurofins
Chemisch				afh. van lutum%, os% en bouwplan		afh. Van lutum% en os%		Handboek Bodem en Bemesting / Adviesbasis Bemesting
Chemisch	10	Stikstof totaal (N-totaal, kg ha^{-1})	Kjeldahl	3110 – 3890	n.b.	n.b.	1410 – 2060	Eurofins
Chemisch	11	Potentieel mineraliseerbare N (PMN, mg kg^{-1})	NIRS	60 – 80	n.b.	n.b.	125 – 175	Eurofins
Chemisch	12	Fosfaatvoorraad (P-Al, mg P_2O_5 100g^{-1})	Extractie in ammoniumlactaat-azijnzuur	31 – 62	34 – 75	19 – 57	30 – 90	Rutgers et al., 2007
Chemisch				n.b.	n.b.	afh. van P-beschikbaar		Adviesbasis Bemesting
Chemisch		Fosfaatvoorraad (P-Al, kg ha^{-1})		355 – 620	n.b.	n.b.	150 – 215	Eurofins
Chemisch		Fosfaatvoorraad (Pw, mg 100 ml^{-1} grond)	Extractie in water	25 zeeklei en zeezand, 30 overige grondsoorten		n.b.	n.b.	Handboek Bodem en Bemesting
Chemisch		Fosfaat beschikbaar (P-$CaCl_2$, kg ha^{-1})	Extractie in $CaCl_2$	5.4 - 9.1	n.b.	n.b.	2.8 - 4.1	Eurofins
Chemisch	13	Kalivoorraad (mmol+ kg^{-1}, kg ha^{-1})	NIRS	335 – 475	n.b.	n.b.	155 – 215	Eurofins
Chemisch		Kali beschikbaar (kg ha^{-1})	Extractie in $CaCl_2$	210 – 330	n.b.	n.b.	95 – 135	Eurofins
Chemisch		Kalivoorraad K-HCl (mg 100 g^{-1})	extractie in HCl en oxaalzuur	16-20	13-17	n.b.	n.b.	Handboek Bodem en Bemesting
Alg	17	Visuele beoordeling (fysisch-chemisch-biologisch): aggregaten, horizonten, reductievlekken, bewortelingsdiepte en –patroon	Visueel	minimaal 25% kruimelstructuur, 0-75% afgerond-blokkige elementen.	minimaal 25% kruimelstructuur, 0-75% afgerond-blokkige elementen.		minimaal 50% kruimelstructuur, 30% afgerond-blokkige en maximaal 20% scherpblokkige elementen.	Koopmans en Brands, 2002; Van Eekeren & Bokhorst, 2009

Annex 4: Framework for measuring quality of employment[75]

Quality of employment is an important issue for society, policy makers, governments and researchers. Employment is key to the social and economic advancement of workers and provides them with a sense of identity, but it may also be associated with risks for health and well-being. The dynamic development of labour markets can be accompanied by challenges concerning the quality of employment that call for statistical measurement. The Handbook for Measuring Quality of Employment, A Statistical Framework was prepared by the Expert Group on Measuring Quality of Employment, established by the Bureau of the Conference of European Statisticians (CES). It aims at providing a clear and coherent structure for measuring quality of employment. Quality of employment is approached as a multidimensional concept, characterised by different elements, which relate to human needs in various ways. To cover all relevant aspects, the framework identifies seven dimensions and twelve sub-dimensions of quality of employment as illustrated in figure 7.

Figure 7: Seven dimensions of quality of employment.

For each dimension and sub-dimension, the framework presents a number of statistical indicators that may be produced. For Dutch agriculture objectives can be set along these seven dimensions as illustrated in table 9.

[75] UNECE Expert Group on Measuring Quality of Employment. (2013). Draft statistical framework for measuring quality of employment. *Nineteenth International Conference of Labour Statisticians*,

Table 9. Quality of employment objectives for Dutch Agrigulture

Dimension	Farm level goal	System level goal (NL)
Safety and ethics	• Farmers and farm workers are not exposed to hazardous chemicals • Number of sick days per employee per year as a result of occupational injury is 0	• Rate of fatal occupational injuries in the sector is 0 • No gender pay gap in the sector
Income and benefits	• Farmers and farm workers earn at least a minimum income	
Working hours and balancing work and non-working life	• Farmers and their family members do not work extra jobs out of necessity	
Security of employment and social protection	• Farm workers have formal contracts	
Social dialogue	• Farmers and farm workers can be members of unions or other collective bargaining associations	
Skills development and training		• tbd
Workplace relationships and work motivation		• > …% of farmers and agricultural workers are satisfied with their jobs and feel they do useful work

Annex 5: Overview of SDGs addressed with regenerative agriculture

- SDG 2: zero hunger
  - 2.4 (ensure sustainable food production systems and implement resilient agricultural practices)
- SDG 3: good health and well-being
  - 3.9 (substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination)
- SDG 6: clean water and sanitation
  - 6.3 (improve water quality by reducing pollution),
  - 6.4 (ensure sustainable withdrawals and supply of freshwater)
  - 6.6 (protect and restore water-related ecosystems)
- SDG 8: decent work and economic growth
  - 8.2 (achieve higher levels of economic productivity through diversification, technological upgrading and innovation)
- SDG 12: responsible consumption and production
  - 12.2 (achieve the sustainable management and efficient use of natural resources),
  - 12.3 (reduce food losses along production and supply chains, including post-harvest losses),
  - 12.4 (achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment)
- SDG 13: climate action
  - 13.1 (strengthen resilience and adaptive capacity to climate-related hazards and natural disasters)
- SDG 14: life below water
  - 14.1 (prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution)
- SDG 15: life on land
  - 15.1 (ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services)
  - 15.2 (promote the implementation of sustainable management of all types of forests)
  - 15.3 (restore degraded land and soil)
  - 15.5 (take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species)