

Unlocking agroecological transition at territorial scale with digital twins : Illustration with a Belgian case study



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ULiège – Gembloux Agro-Bio Tech
Plant sciences Axis – Crop Science Lab



Cropping systems & Food systems



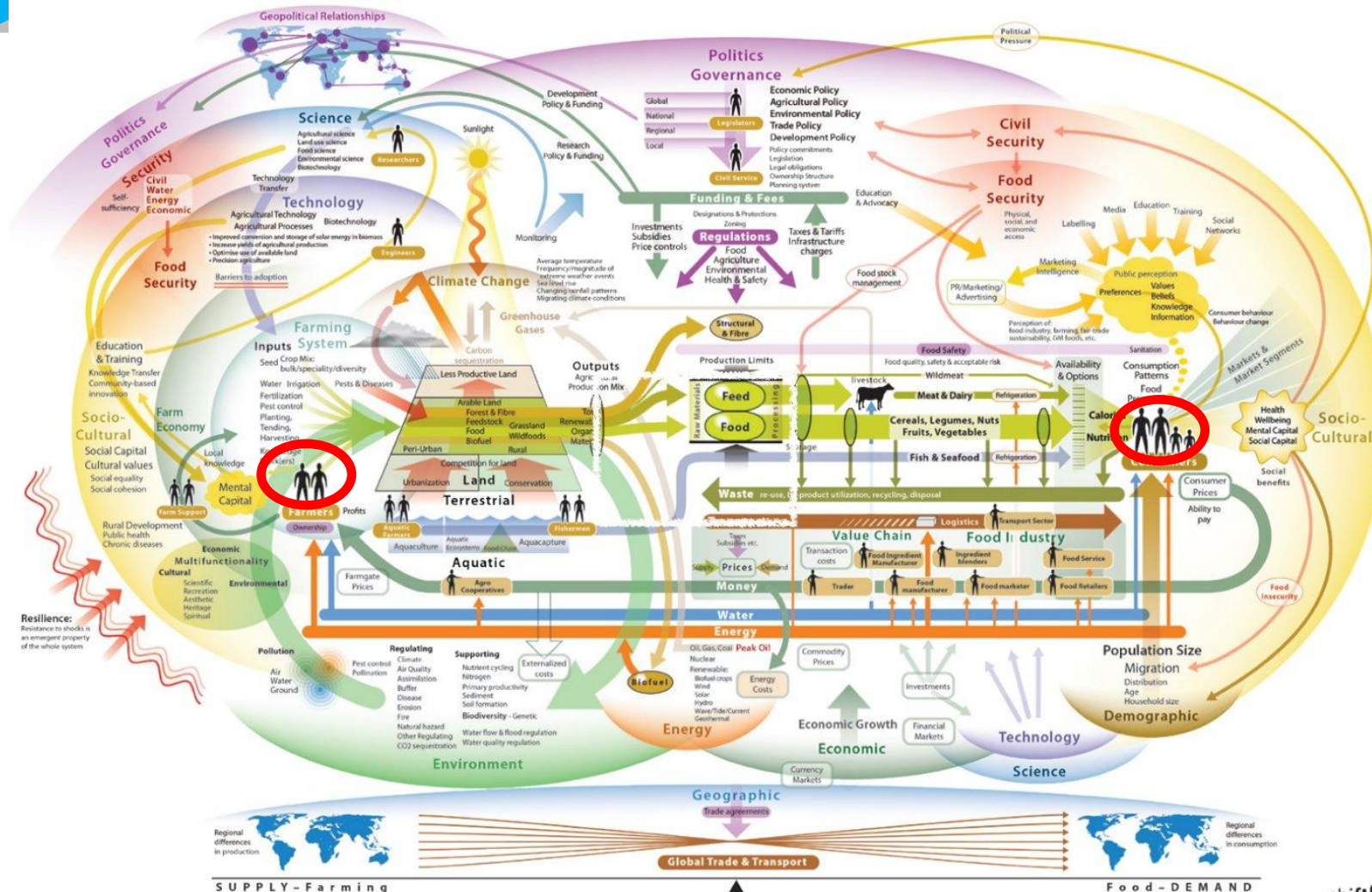
*« In everything there is a
share of everything »*

[Anaxagoras]



Over the course of History, people across the world have developed a wide variety of food systems





100 years of “innovation” in agriculture have reshaped the world :

- Motorization
- Mecanization
- Chemistry
 - Fertilizers
 - Pesticides (crop and animal)
- Selection
 - Variety
 - Breed
- Specialization



... And later on: digitalization

Moto-Mecanization



July of 1941 in Walla Wall County, Washington State.

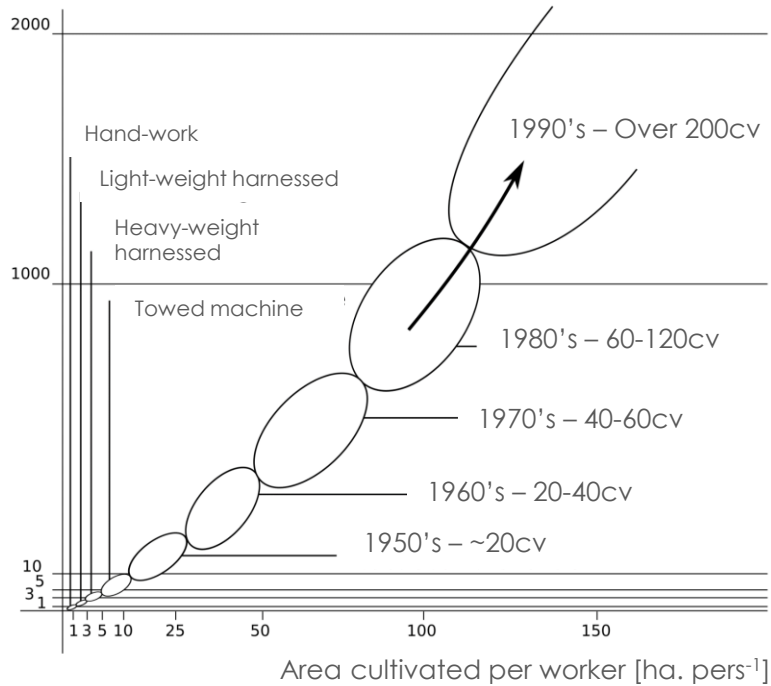
Moto-Mecanization



July of 1941 in Walla Wall County, Was

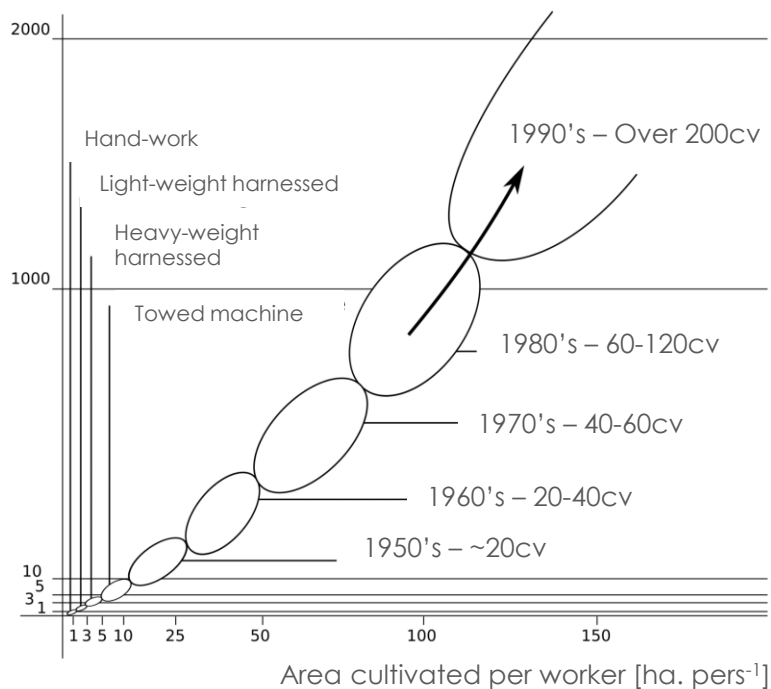
Moto-Mecanization

Amount of grain produced per worker [t.pers⁻¹]



Moto-Mecanization

Amount of grain produced per worker [t.pers⁻¹]

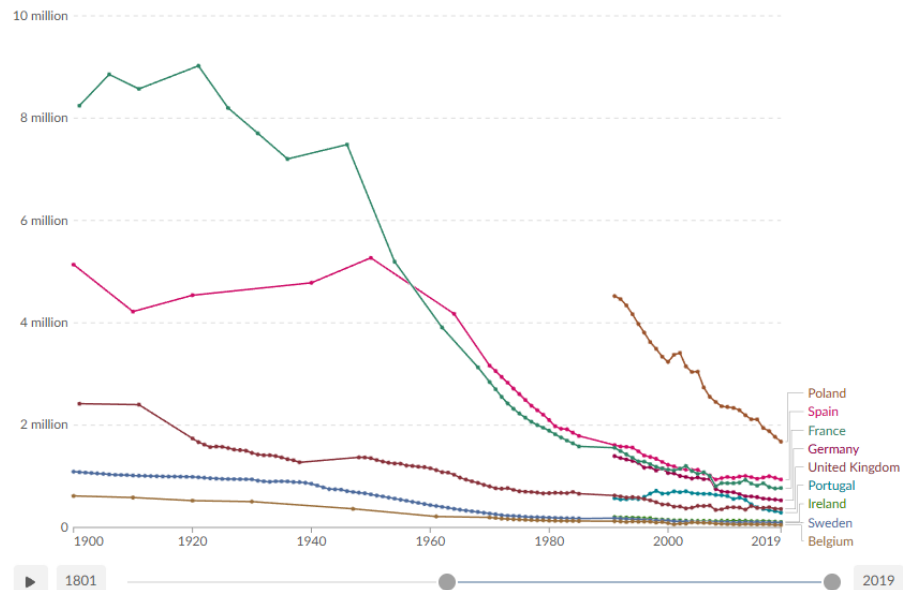


Number of people employed in agriculture, 1900 to 2019

Agriculture includes the cultivation of crops and livestock production, as well as forestry, hunting, and fishing. Employment includes anyone engaged in any activity to produce goods or services for pay or profit.

Our World in Data

Table Map Line Bar



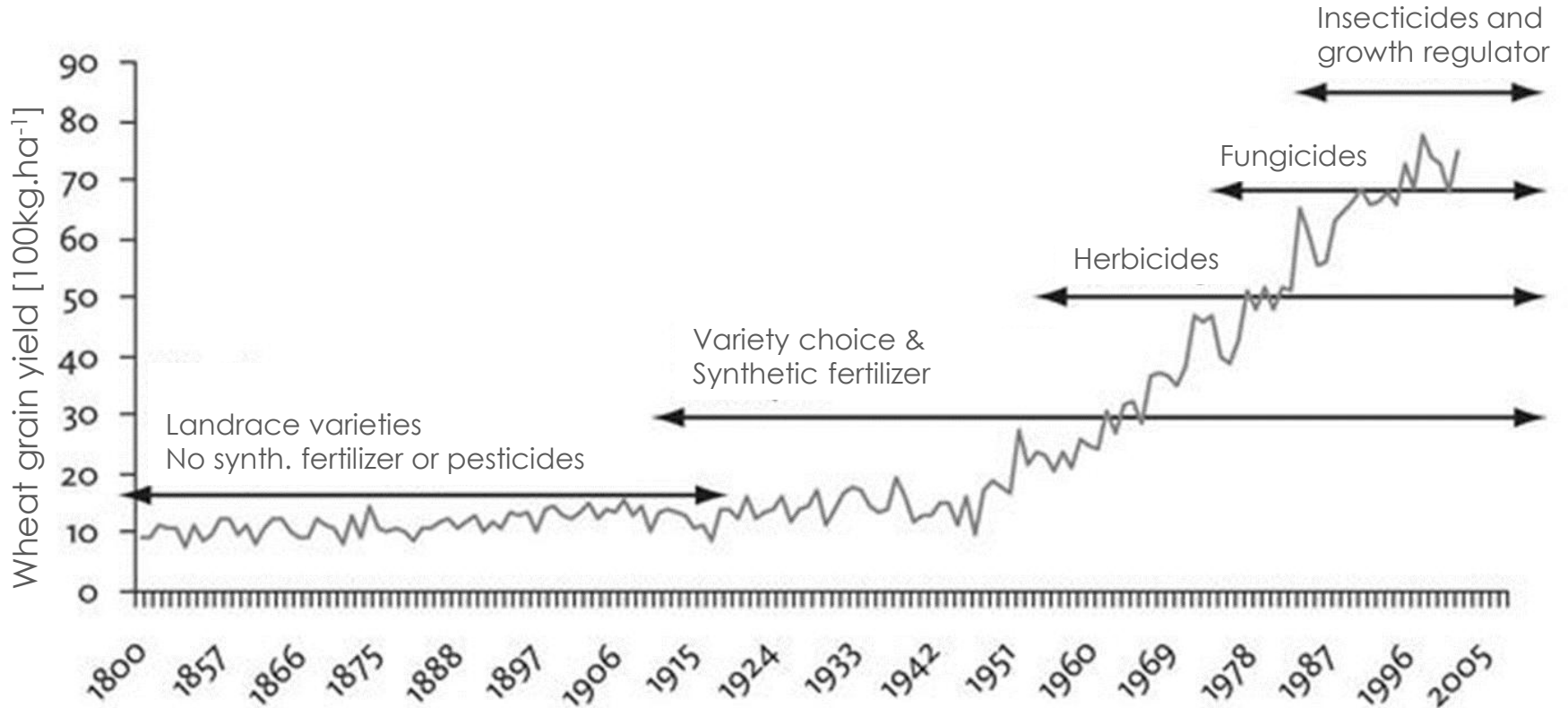
Data source: Our World in Data based on International Labor Organization (via the World Bank) and historical sources - [Learn more about this data](#)

OurWorldinData.org/employment-in-agriculture | CC BY



Related: [Employment in agriculture: Our data sources and definition](#)

Chemistry x Variety choice



Variety choice

SCIENTIFIC REPORTS

OPEN Yield trends, variability and stagnation analysis of major crops in France over more than a century

Received: 11 June 2018
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Published online: 15 November 2018

Bernhard Schaubberger^{1,2}, Tamara Ben-Ari^{3,4}, David Makowski^{3,4}, Tomomichi Kato^{5,6}, Hiromi Kato⁷ & Philippe Ciais⁸

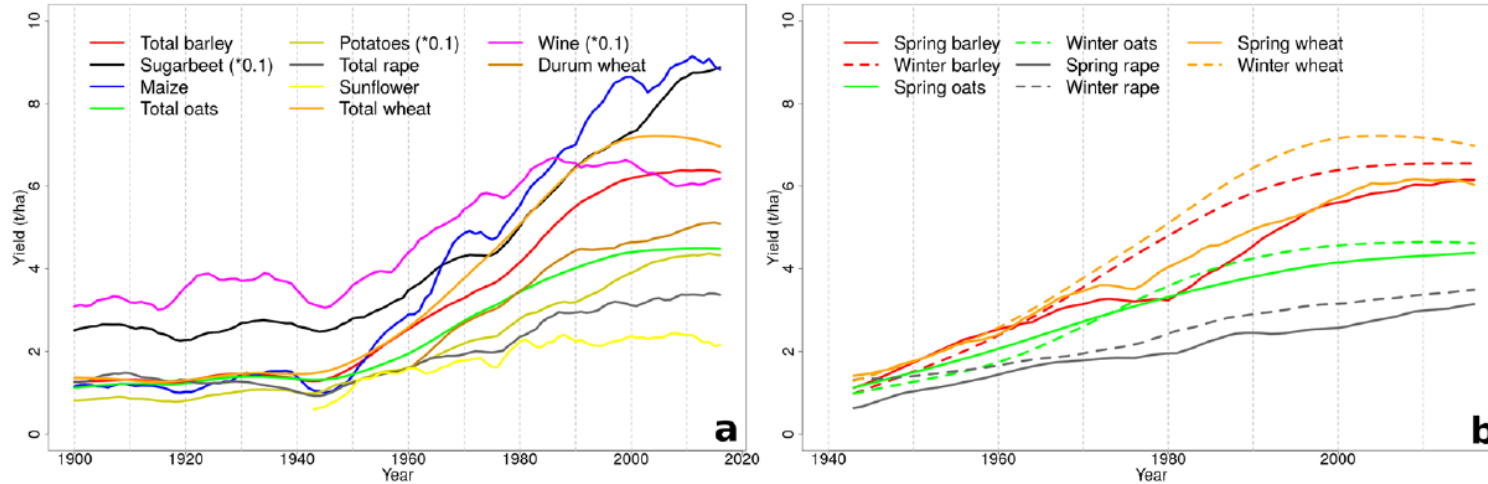


Figure 1. Trends and growth rates for national yields of staple French crops in the 20th and 21st century. **(a)** Yield trends, for one-season and season-aggregated crop species (1900–2016). **(b)** Yield trends, for spring and winter crop types (1943–2016).

Variety choice

Breeding is probably what prevent yield from declining...



Variety choice

Breeding is probably what prevent yield from declining...

... but we might have too few genetic diversity and a co-dependence of selection with inputs use

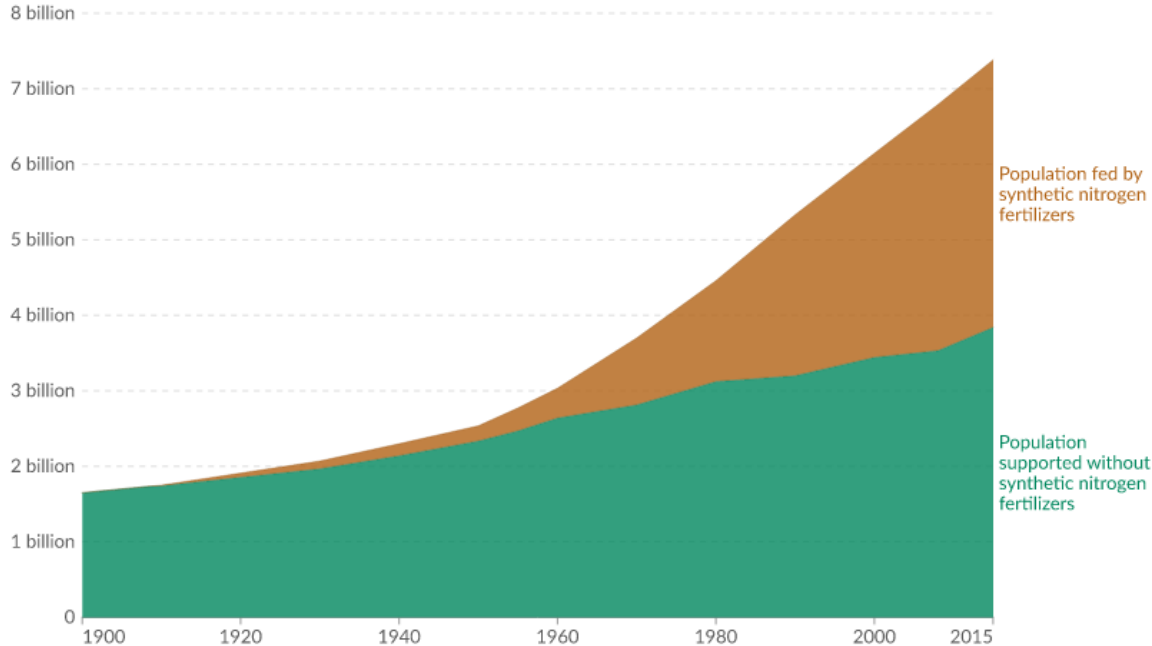


Chemistry

World population supported by synthetic nitrogen fertilizers

Our World
in Data

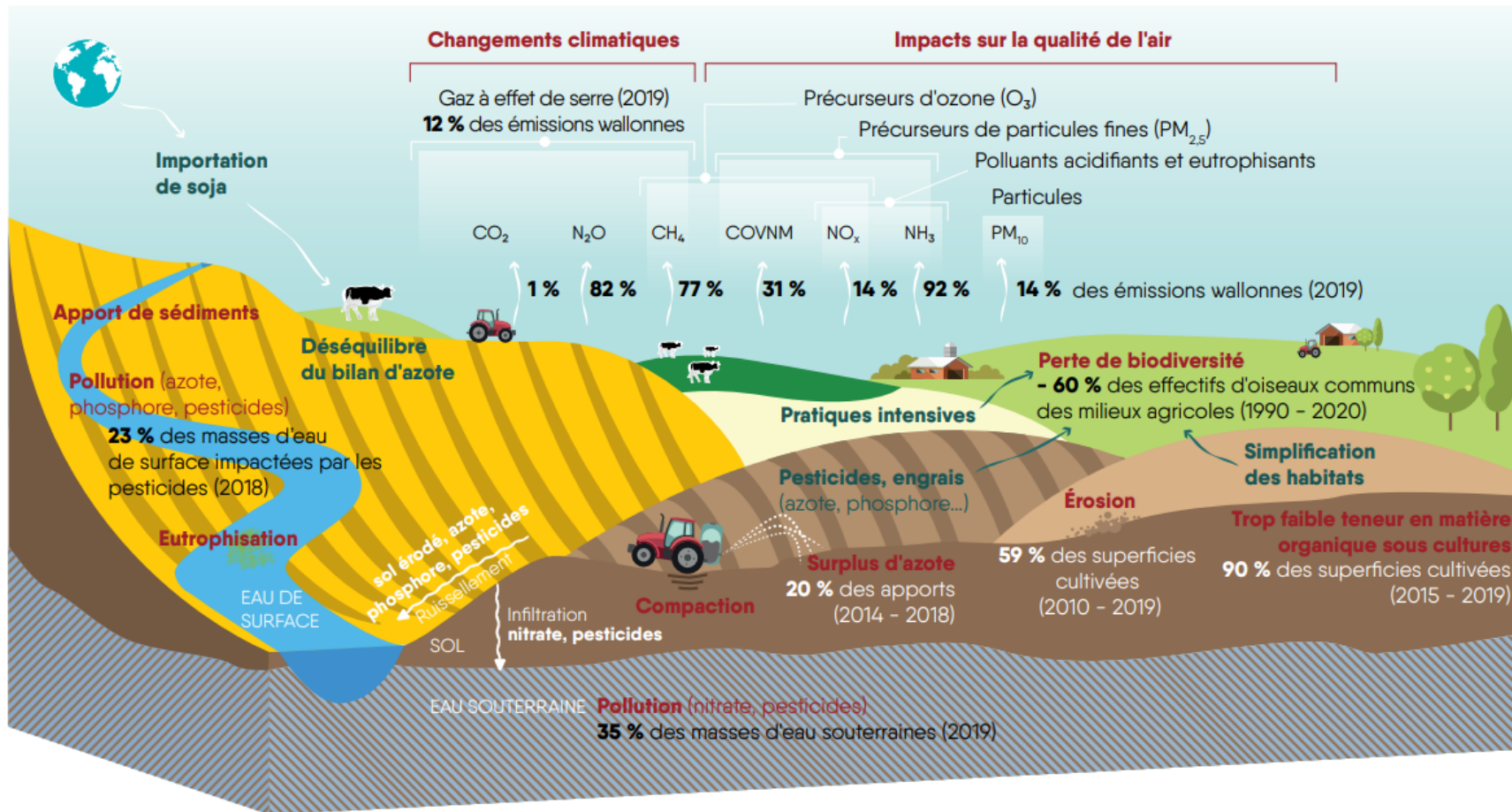
Best estimates project that just over half of the global population could be sustained without reactive nitrogen fertilizer derived from the Haber-Bosch process.



Data source: Erisman et al. (2008); Smil (2002); Stewart (2005)

OurWorldinData.org/fertilizers | CC BY

Virtually, ~50% of the Nitrogen in your body has gone through the process invented +100 years ago by Fritz Haber and Carl Bosch



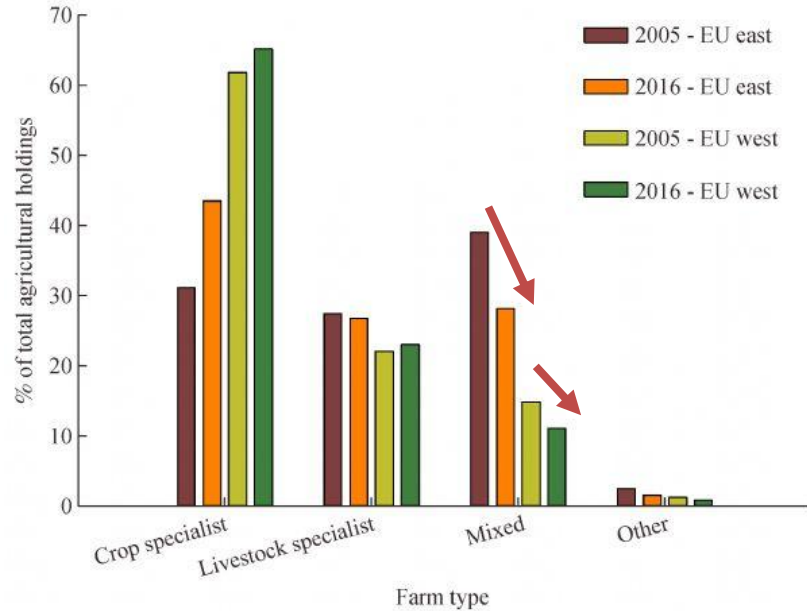
Specialization

1955 → 2005

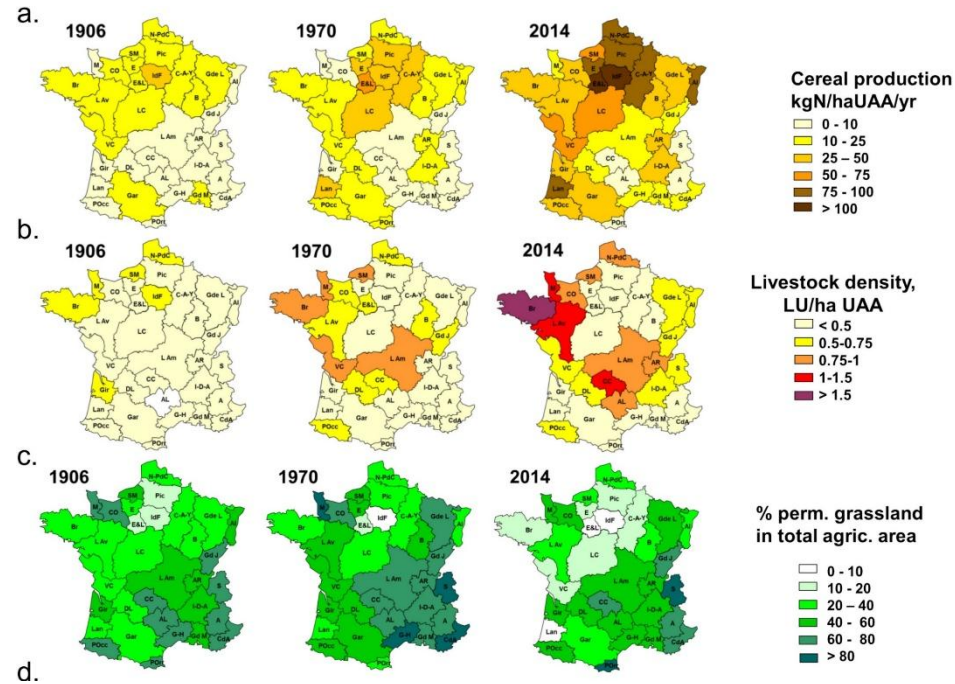


Source: BdOrlino IGN

Specialization



Change in specialized and mixed farm types in selected western and eastern EU countries in 2005 and 2016, in western (EU west) and eastern Europe (EU east). Source from Eurostat



Digitalization

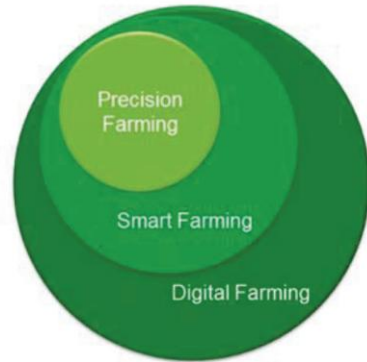


Figure 1. The development of Precision to Digital Farming

Digitalization

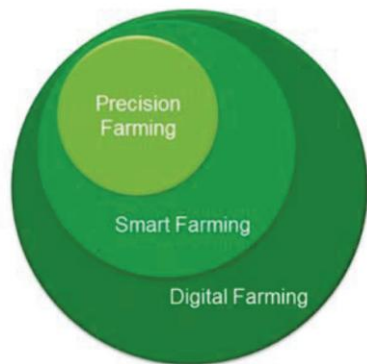
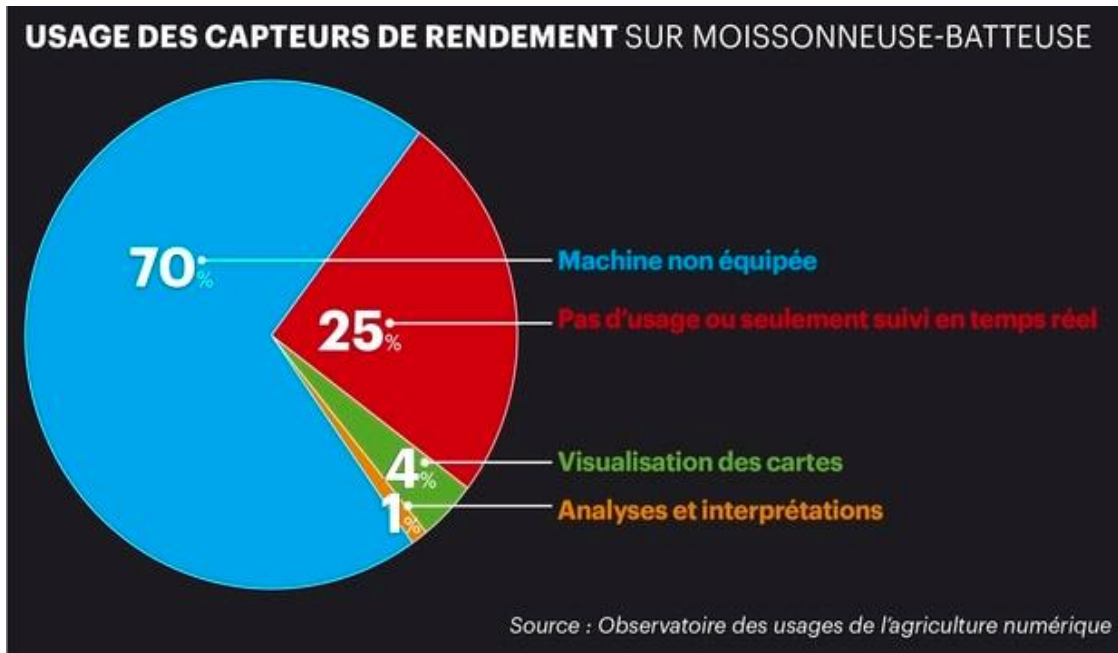


Figure 1. The development of Precision to Digital Farming



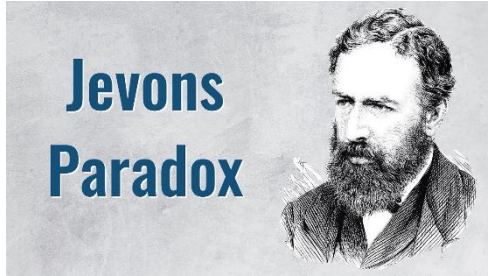
70% unequiped harvester

25% real time visualization

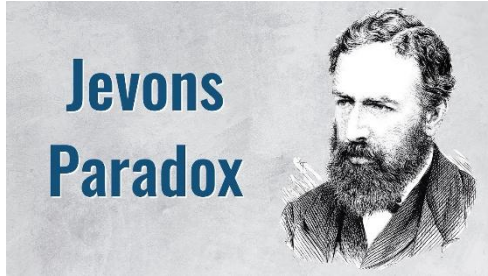
4% post harvest visualization

1% analyse and interpret to adapt managment

Digitalization



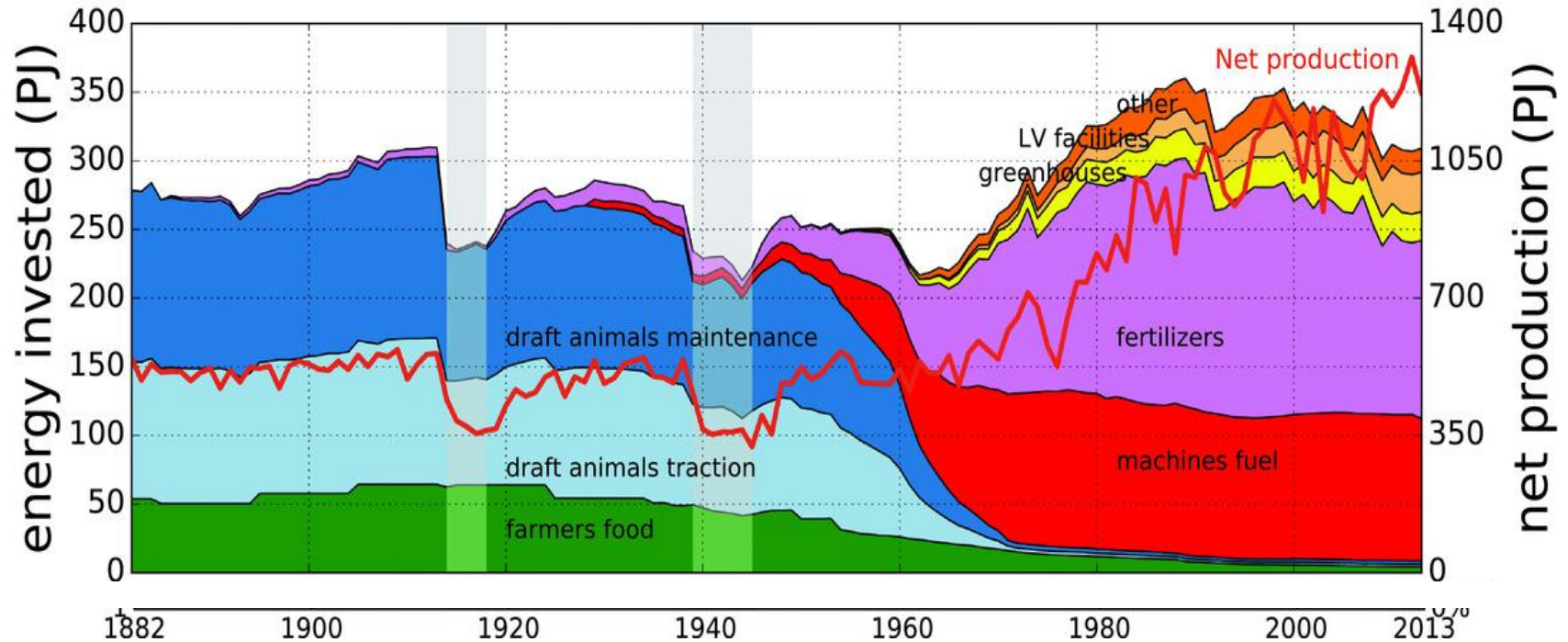
Digitalization



“Setting biogas as sustainable without assessing its sustainability through a full environmental impact assessment risk incentivize a massive scale up of plants, which could lead to an unsustainable lock-in [...]”



The metabolism of agriculture has completely changed !





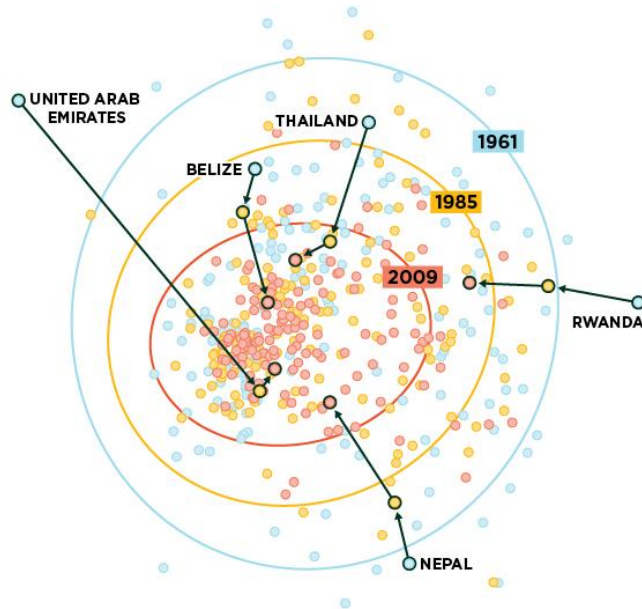
The nap
Vincent van Gogh



The diversity of food diets is slowly eroding !

Each country's food supply composition in contribution to calories in:

● 1961 ● 1985 ● 2009

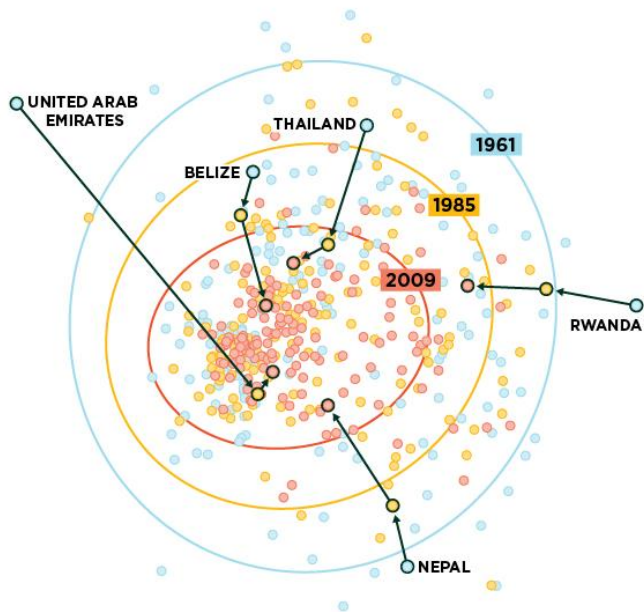


Source: Khoury et al. 2014. Proc. Natl. Acad. Sci. USA.

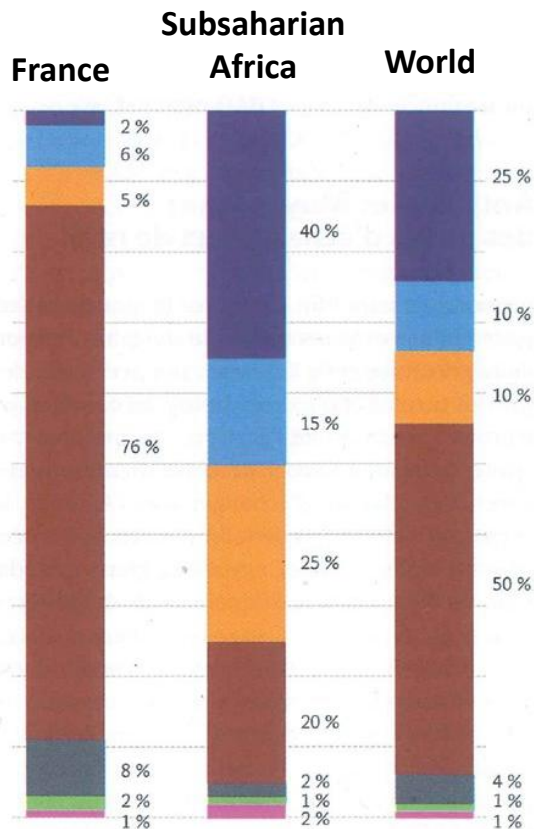
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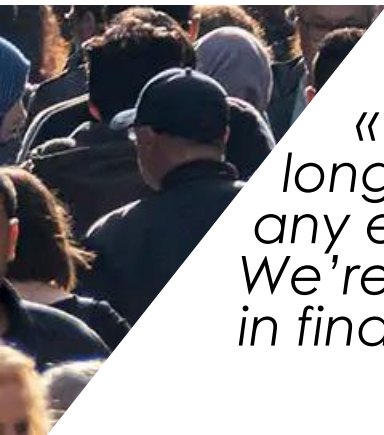
Source: Khoury et al. 2014. Proc. Natl. Acad. Sci. USA.



Agro-industrial model



Time for change ?



« If we've been bamboozled long enough, we tend to reject any evidence of the bamboozle. We're no longer interested in finding our the truth »

[Carl Sagan – the demon-haunted world]

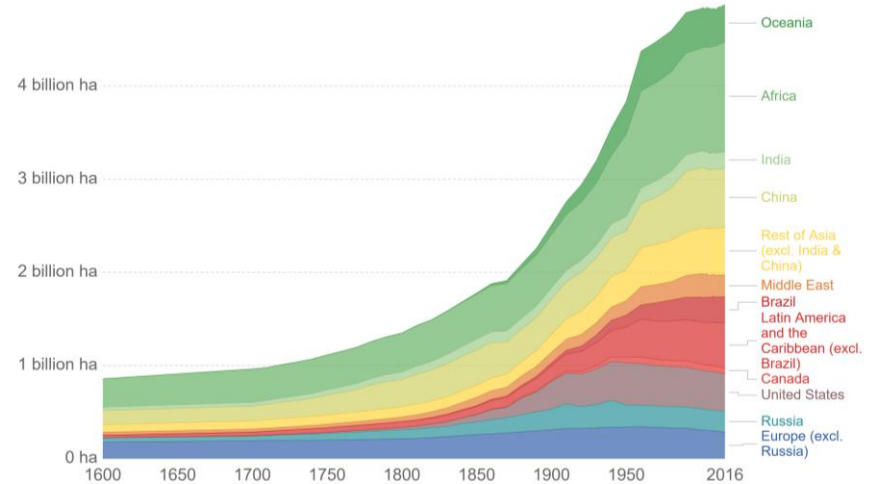




Agricultural area over the long-term

Total areal land use for agriculture, measured as the combination of land for arable farming (cropland) and grazing in hectares.


Our World
in Data



Source: History Database of the Global Environment (2017)

OurWorldInData.org/yields-and-land-use-in-agriculture/ • CC BY

Agricultural area are almost at their maximal expansion !
More than ever the narrative keeps to be « improve yield levels ».



Our plates are not neutral

- Agriculture uses 50% of habitable land, with $\frac{3}{4}$ dedicated exclusively to livestock.
- Agriculture and forestry account for 23% of anthropogenic greenhouse gas emissions.
- Agriculture is the sector being the largest contributor to CH₄ and N₂O emissions.
- Agriculture is the biggest driver of biodiversity loss !
- ...

« Yeahh... maybe... but we feed the world ! »

[Some western farmers, probably]

Do we actually feed the world ??

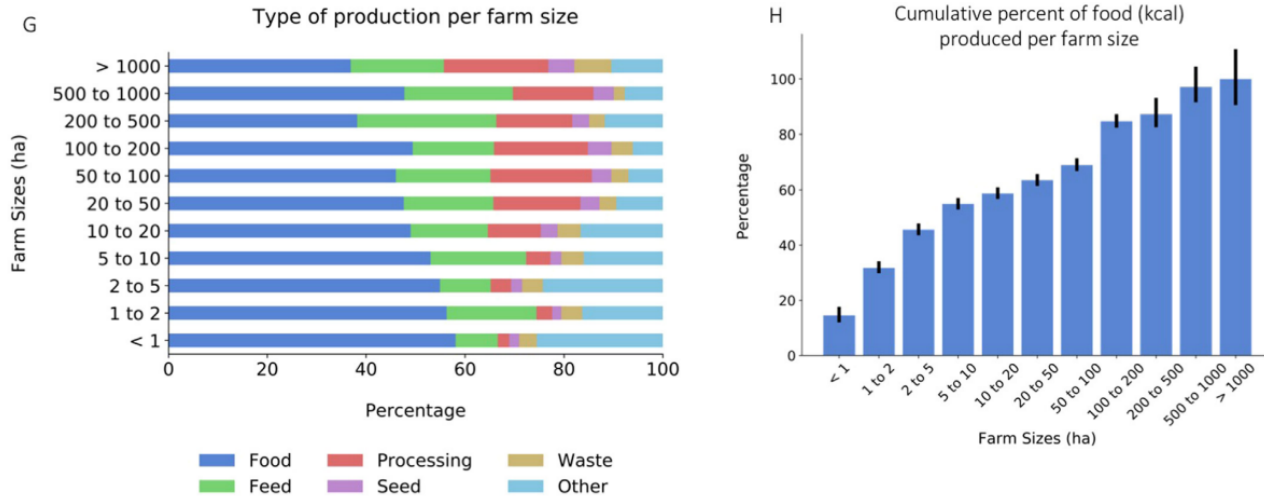


Fig. 2. A-F) Distribution of total global crop production (in kcal equivalents) across farm size groups different uses (e.g., food, feed, other, etc.). Grey shows bootstrapped 95% confidence intervals and red indicates the average. G) Allocation of use of production within each farm size class. H) Cumulative percent of global food production by farm size group with 95% confidence intervals. See [Table S1](#) for underlying data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

- +50% of world calories are produced on farm <10ha
- Bigger farm produce :
 - less food
 - more feed
 - more processing

Do we actually feed the world ??

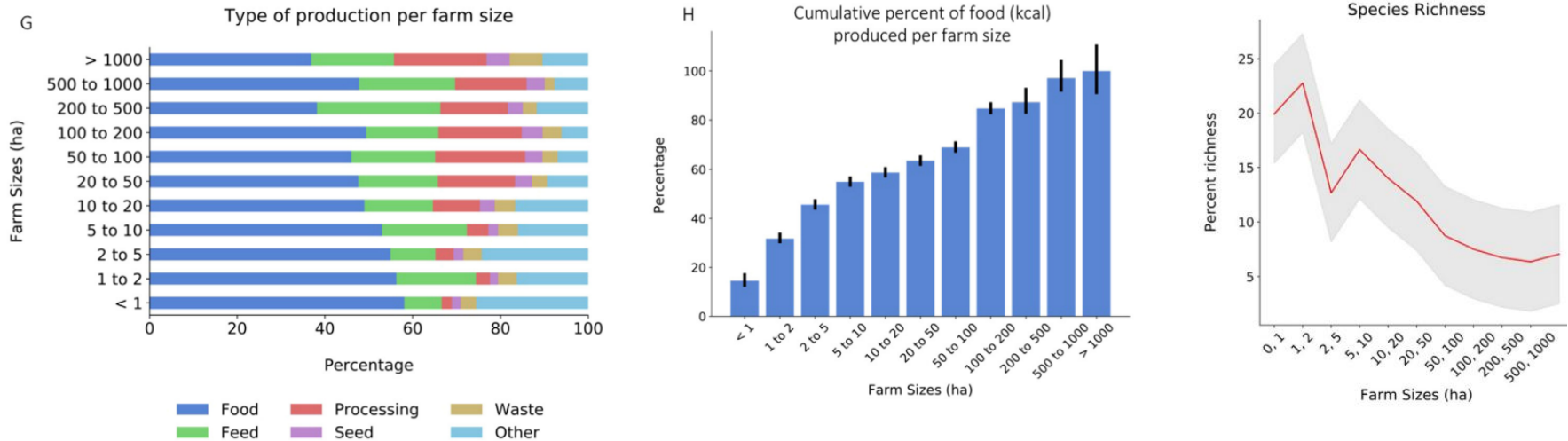
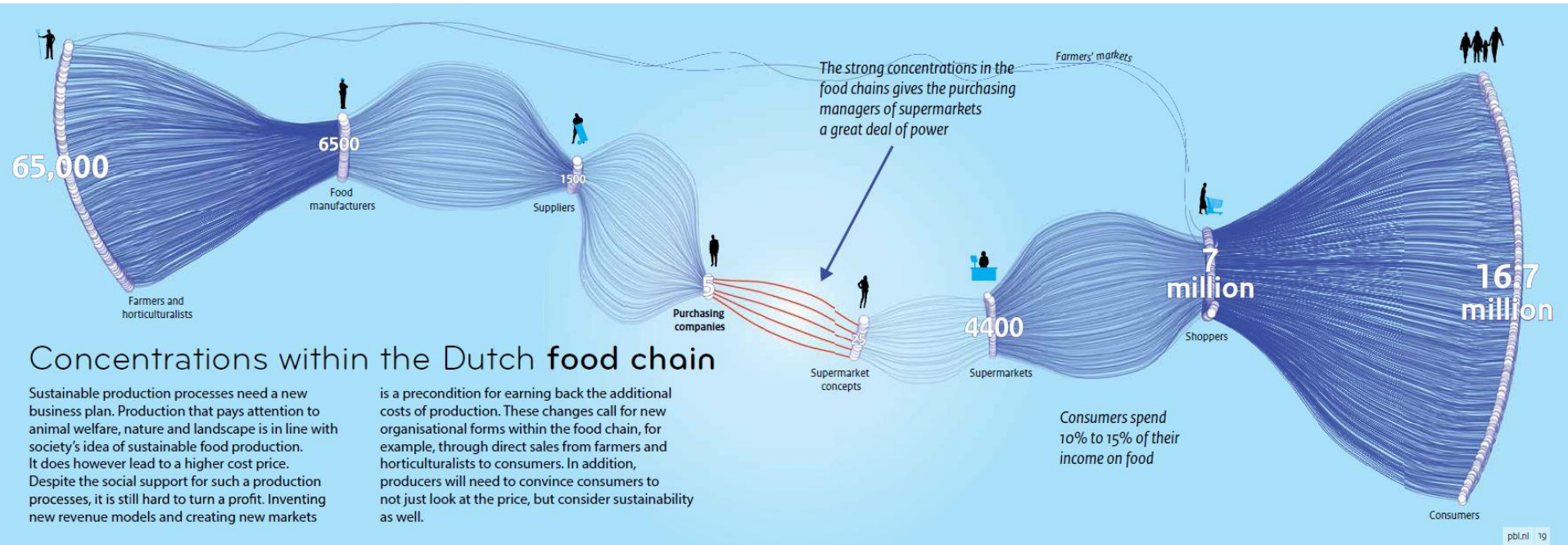


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- The diversity of cultivated species tend to be lower on bigger farms (specialization)

Do we actually feed the world ??



Concentrations within the Dutch food chain

Sustainable production processes need a new business plan. Production that pays attention to animal welfare, nature and landscape is in line with society's idea of sustainable food production. It does however lead to a higher cost price. Despite the social support for such a production processes, it is still hard to turn a profit. Inventing new revenue models and creating new markets

is a precondition for earning back the additional costs of production. These changes call for new organisational forms within the food chain, for example, through direct sales from farmers and horticulturalists to consumers. In addition, producers will need to convince consumers to not just look at the price, but consider sustainability as well.

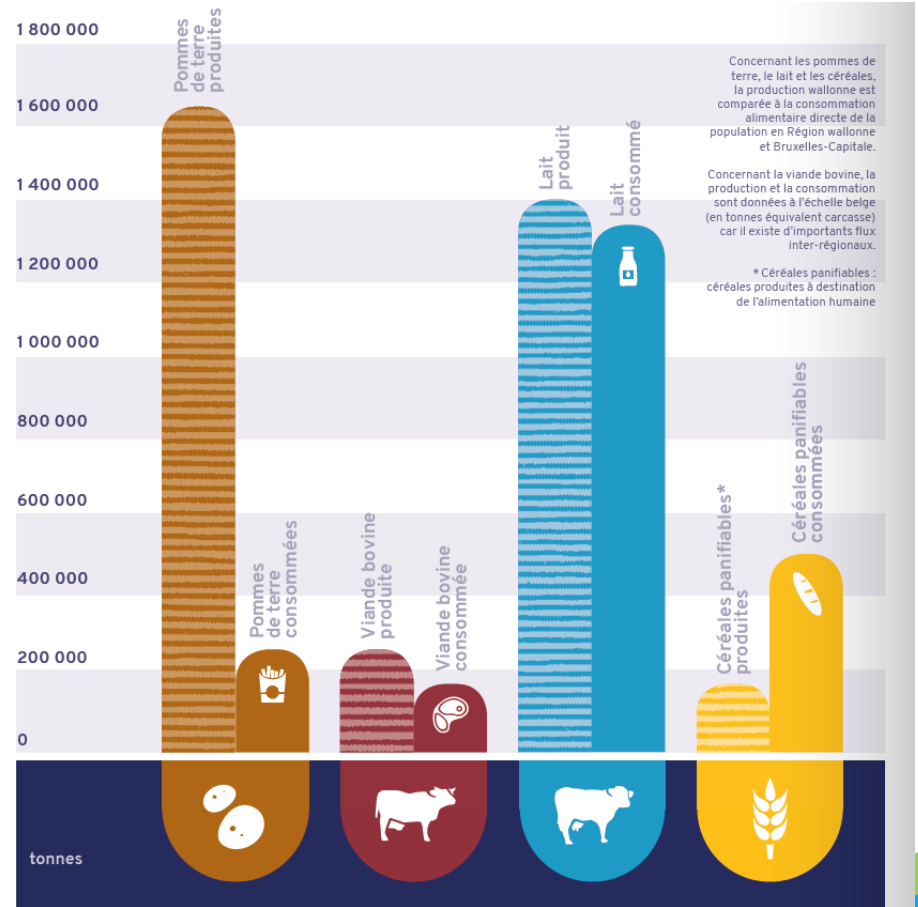
Do we actually feed the world ??

For 100 euros spend on food :

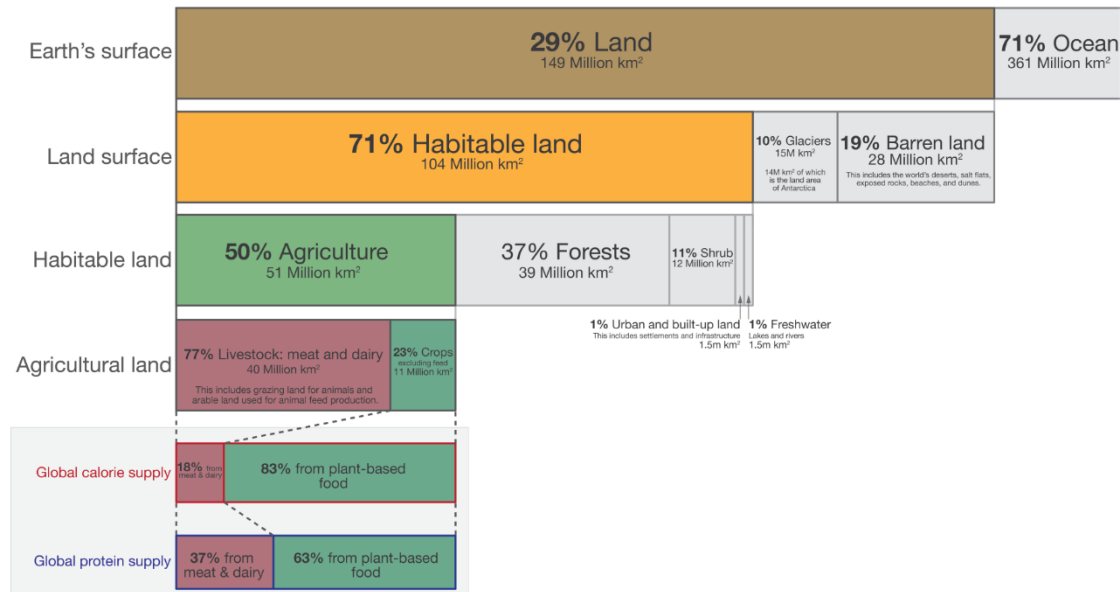
- ~20 euros for the supermarket
- ~15 euros for inputs (fertilizers, pesticides, feed,...)
- ~14 euros for imports
- ~13 euros for food transformation
- ~9 euros in taxes
- ~8 euros for farmers



Imbalance between production and local needs !



Global land use for food production

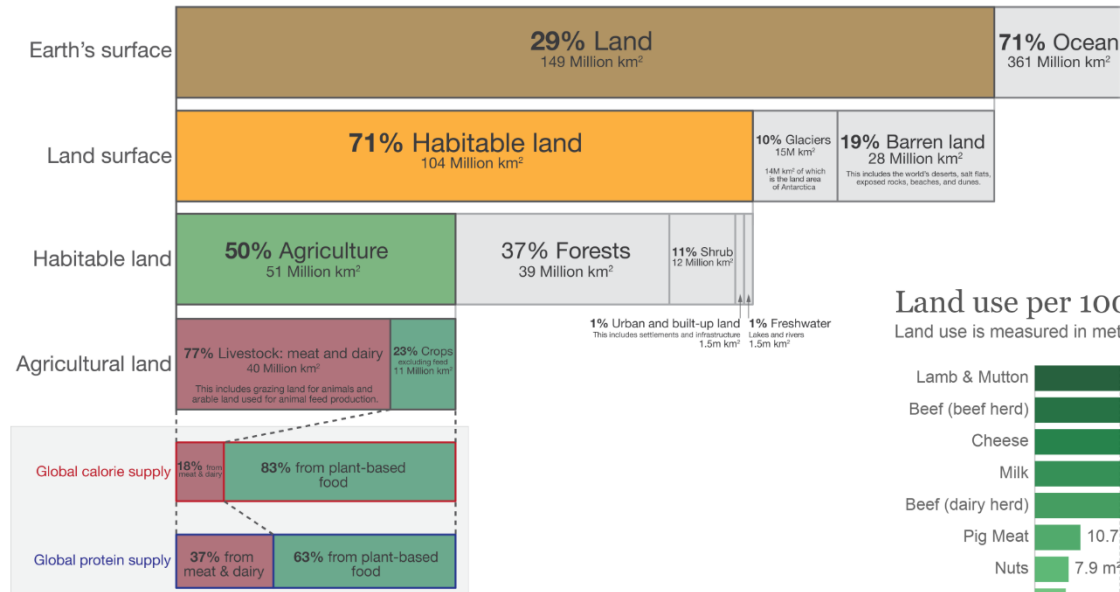


Data source: UN Food and Agriculture Organization (FAO)

OurWorldinData.org – Research and data to make progress against the world's largest problems.

Licensed under CC-BY by the authors Hannah Ritchie and Max Roser in 2019.

Global land use for food production

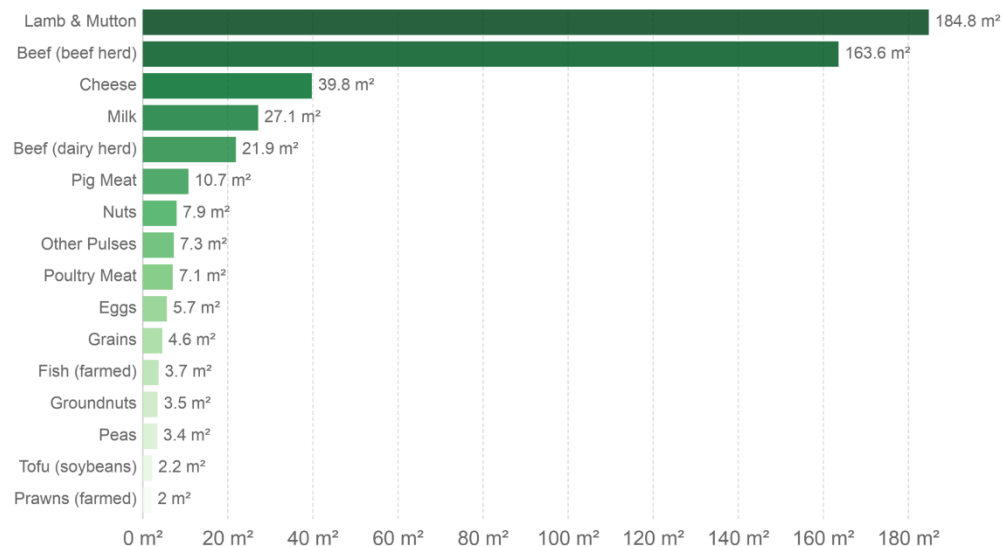


Data source: UN Food and Agriculture Organization (FAO)
OurWorldInData.org – Research and data to make progress against the world's largest problems.

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Land use per 100 grams of protein

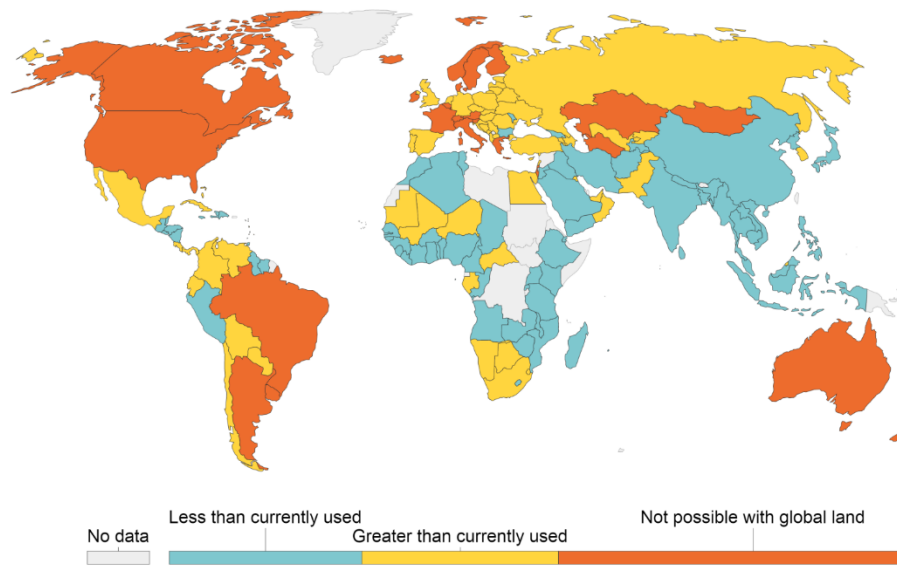
Land use is measured in meters squared (m²) per 100 grams of protein across various food products.



Source: Poore, J., & Nemecek, T. (2018). Additional calculations by Our World in Data.
Note: Data represents the global average land use of food products based on a large meta-analysis of food production covering 38,700 commercially viable farms in 119 countries.
OurWorldInData.org/environmental-impacts-of-food • CC BY

Share of global habitable land needed for agriculture if everyone had the diet of...

The percentage of global habitable land area needed for agriculture if the total world population was to adopt the average diet of any given country, in 2011. The actual proportion of habitable land used for agriculture was 50 percent. Values greater than 100% are not possible within global land constraints.

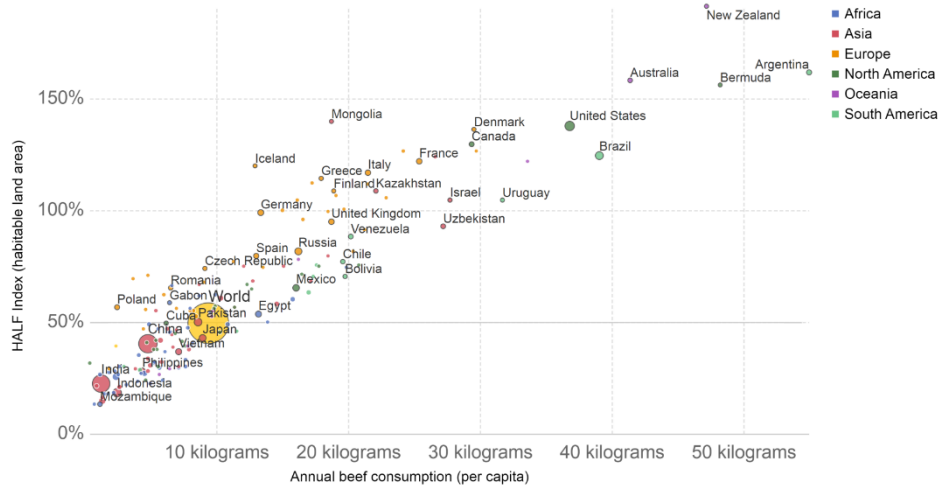


Source: Alexander et al. (2016)

OurWorldInData.org/agricultural-land-by

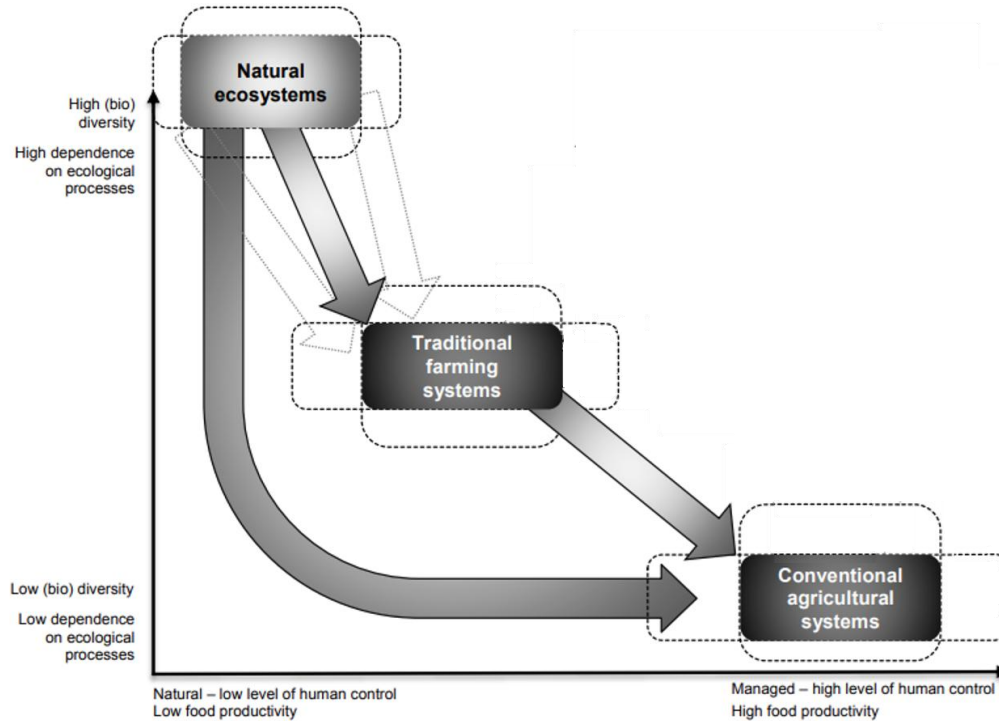
Dietary land use vs. beef consumption, 2011

The percentage of global habitable land area needed for agriculture if the total world population was to adopt the average diet of any given country versus annual per capita beef consumption, measured in kilograms per year. We currently use approximately 50% of habitable land for agriculture, as shown by the grey horizontal line.



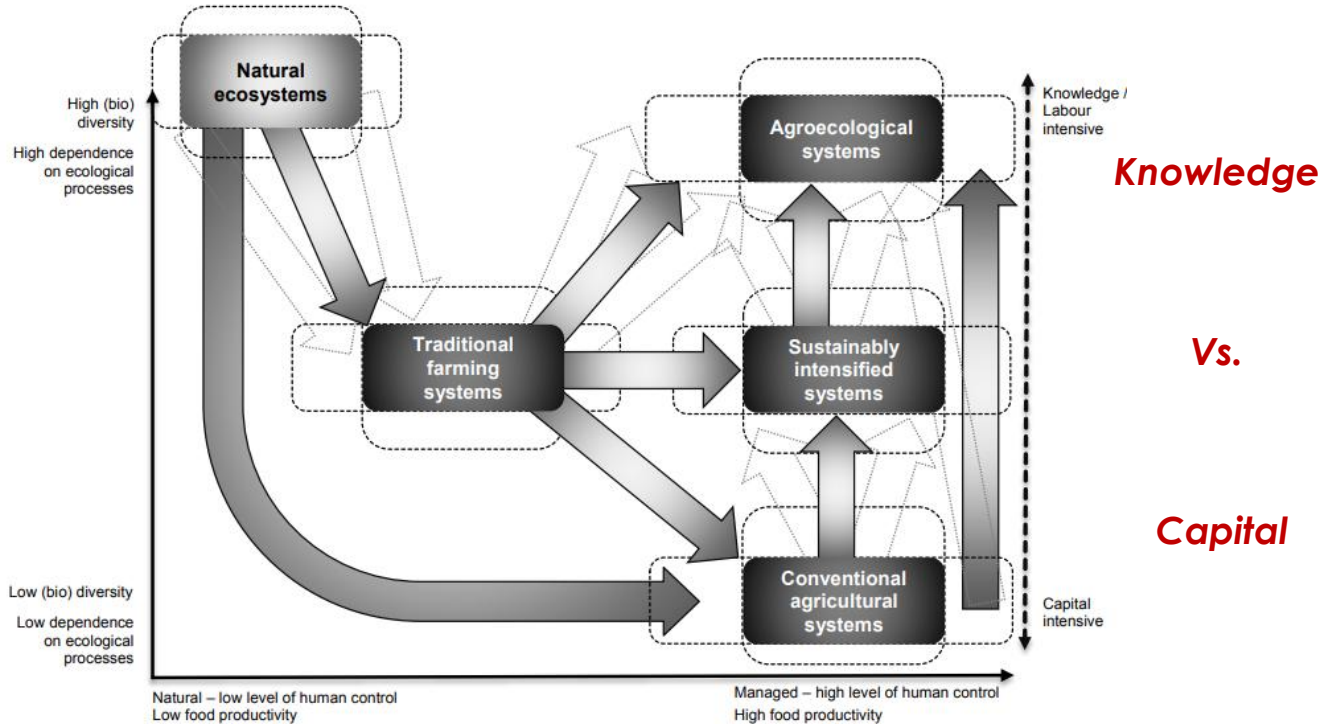
Source: Food Balance Sheets - FAO (2017), HALF Index (Land Use) - Alexander et al. (2016), Population (Gapminder, HYDE(2016) & UN (2019))
 OurWorldInData.org/meat-and-seafood-production-consumption/ • CC BY

Biodiversity



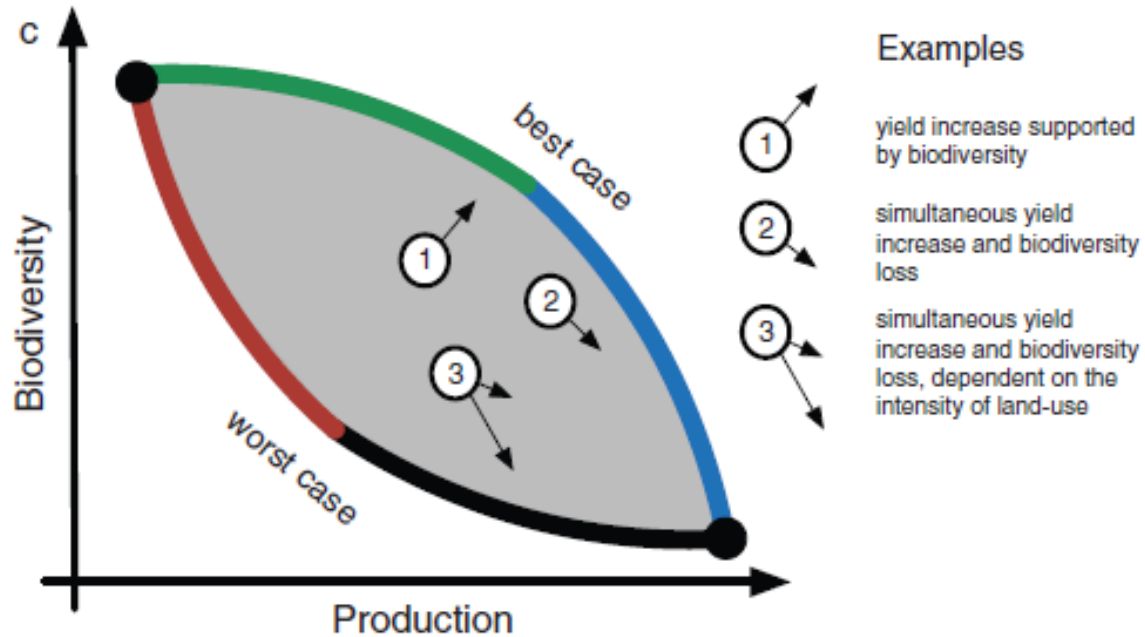
Productivity

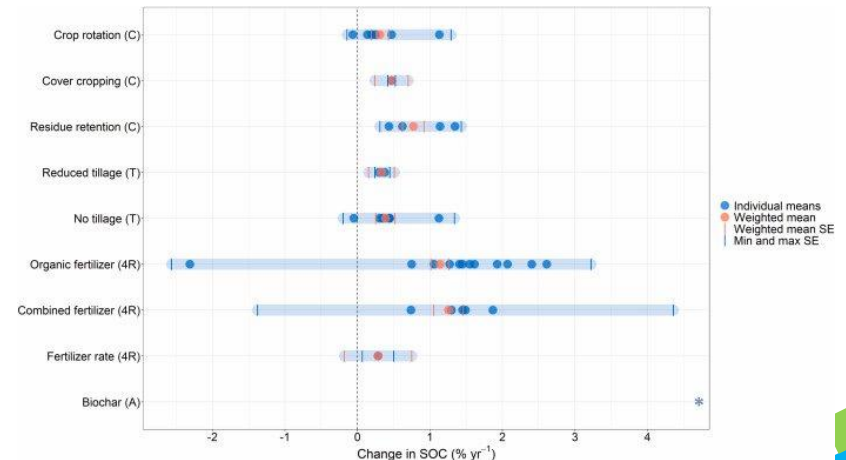
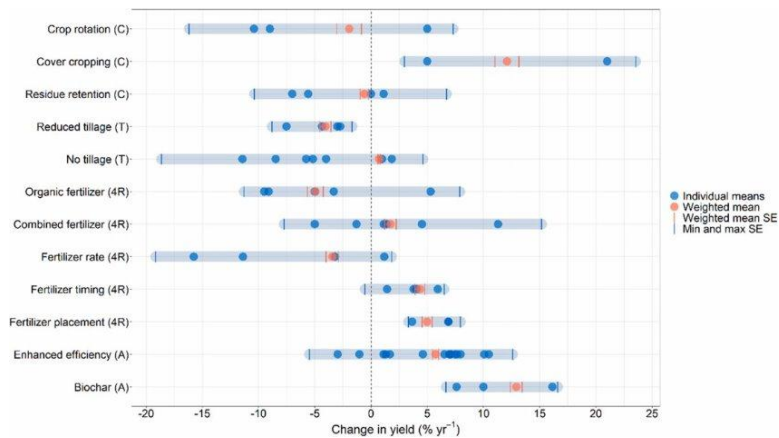
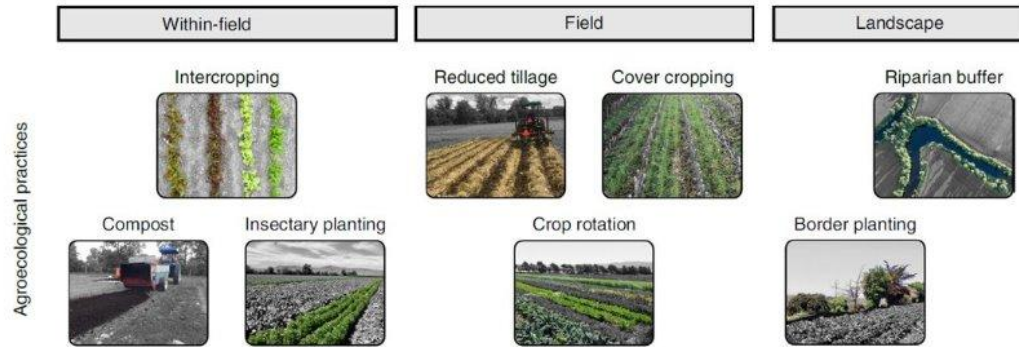
Biodiversity

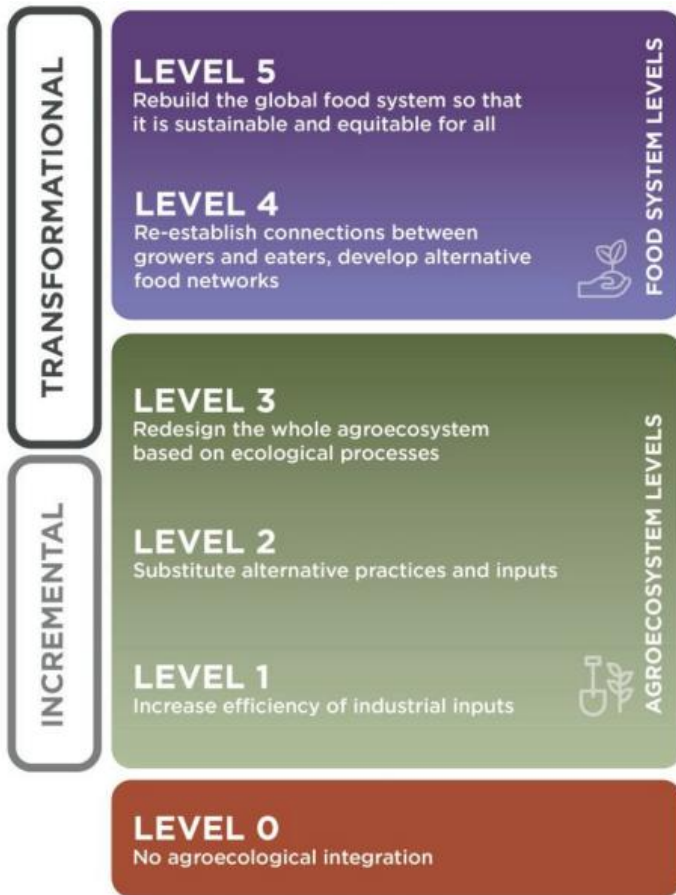


Productivity

- Agroecology is the use of knowledge to bend the curve linking biodiversity to production







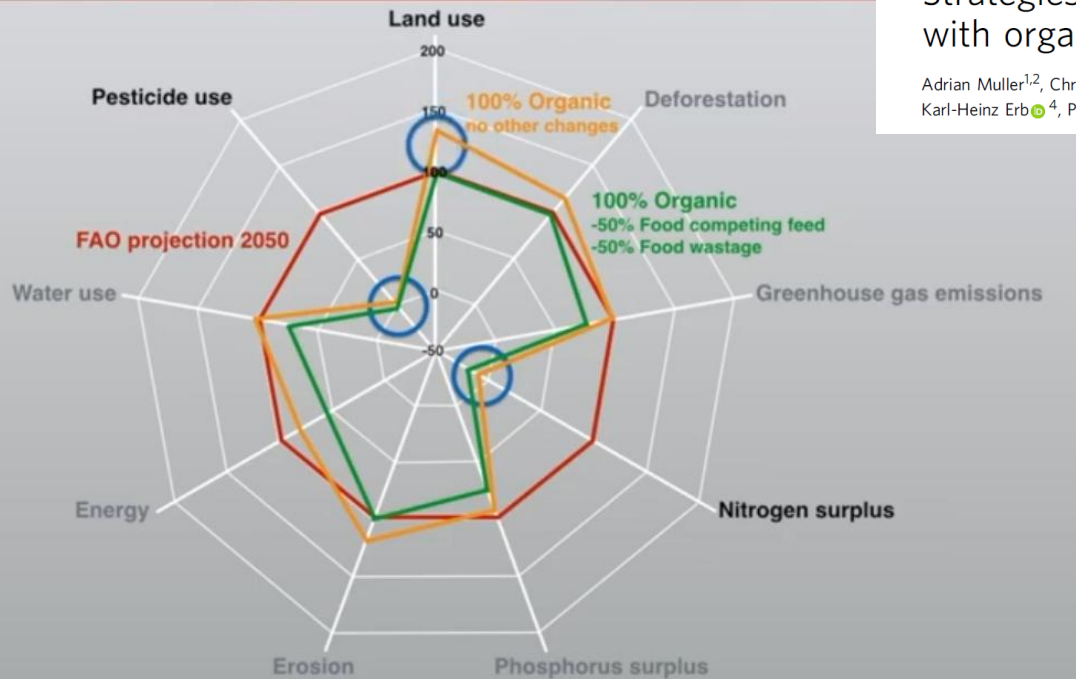
ARTICLE

DOI: 10.1038/s41467-017-01410-w

OPEN

Strategies for feeding the world more sustainably with organic agriculture

Adrian Muller^{1,2}, Christian Schader¹, Nadia El-Hage Scialabba³, Judith Brüggemann¹, Anne Isensee¹, Karl-Heinz Erb⁴, Pete Smith⁵, Peter Klocke^{1,6}, Florian Leiber¹, Matthias Stolze¹ & Urs Niggli¹





Redesigning <Walloon> agriculture in a nutshell

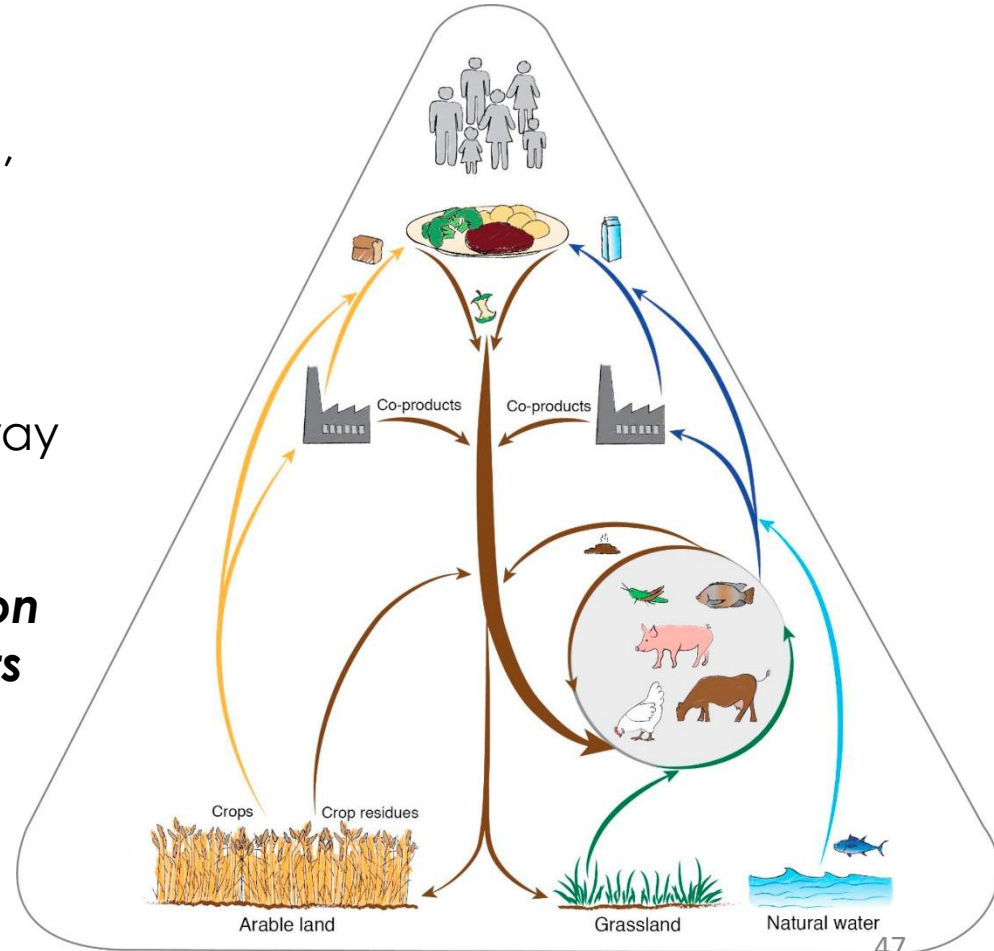


*«We must refocus on
our needs rather than
our desires...»*

[Oliver Hamant – Antidote to the cult of performance]



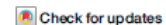
- Agriculture is a complex system where soil, plants, animals, climate, and human activities are interconnected.
- Changes in one given element will not impact the system the same way as another
- Over the past **we've mainly work on efficiencies of specific components**
- A holistic perspective should help design sustainable solutions by considering all interactions.





<https://doi.org/10.1038/s44264-025-00092-y>

Towards sustainable diets and farming systems through land use optimisation



Tom Desmarez¹✉, Jérôme Bindelle^{2,3} & Benjamin Dumont^{1,3}

The industrialised food system poses health and environmental challenges, raising concerns about its sustainability. Addressing these requires region-specific solutions that consider local agronomic and socio-economic conditions. This study examines how transforming the food system impacts land use and self-sufficiency in a defined region of a country. Using Wallonia as a case study, we modelled crop allocation across different pedoclimatic conditions and evaluated three diets—CURRENT, TYFA, and EAT-Lancet—under conventional and organic farming, with 30% or 10% food waste. Our results demonstrate that, regardless of farming practice, Wallonia cannot achieve self-sufficiency under the CURRENT diet. However, adopting the TYFA or EAT-Lancet diets would enable self-sufficiency and spare land for alternative uses, under conventional farming. Food waste reduction was pivotal for enhancing self-sufficiency under organic farming. This research offers a solid foundation for informing agri-food policies in Wallonia and can be extended to other regions seeking to improve local food security.

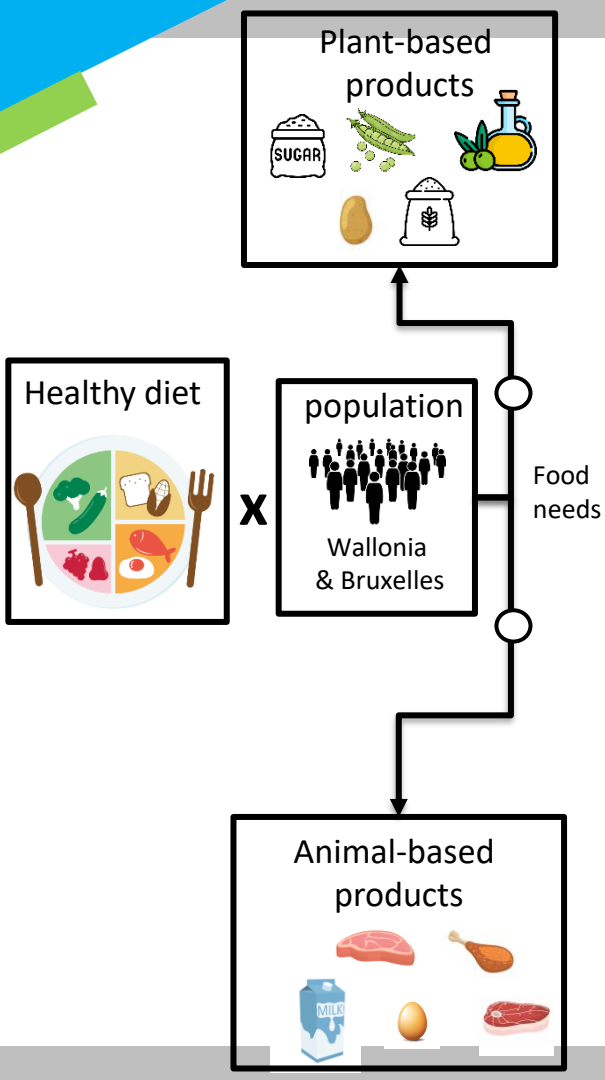


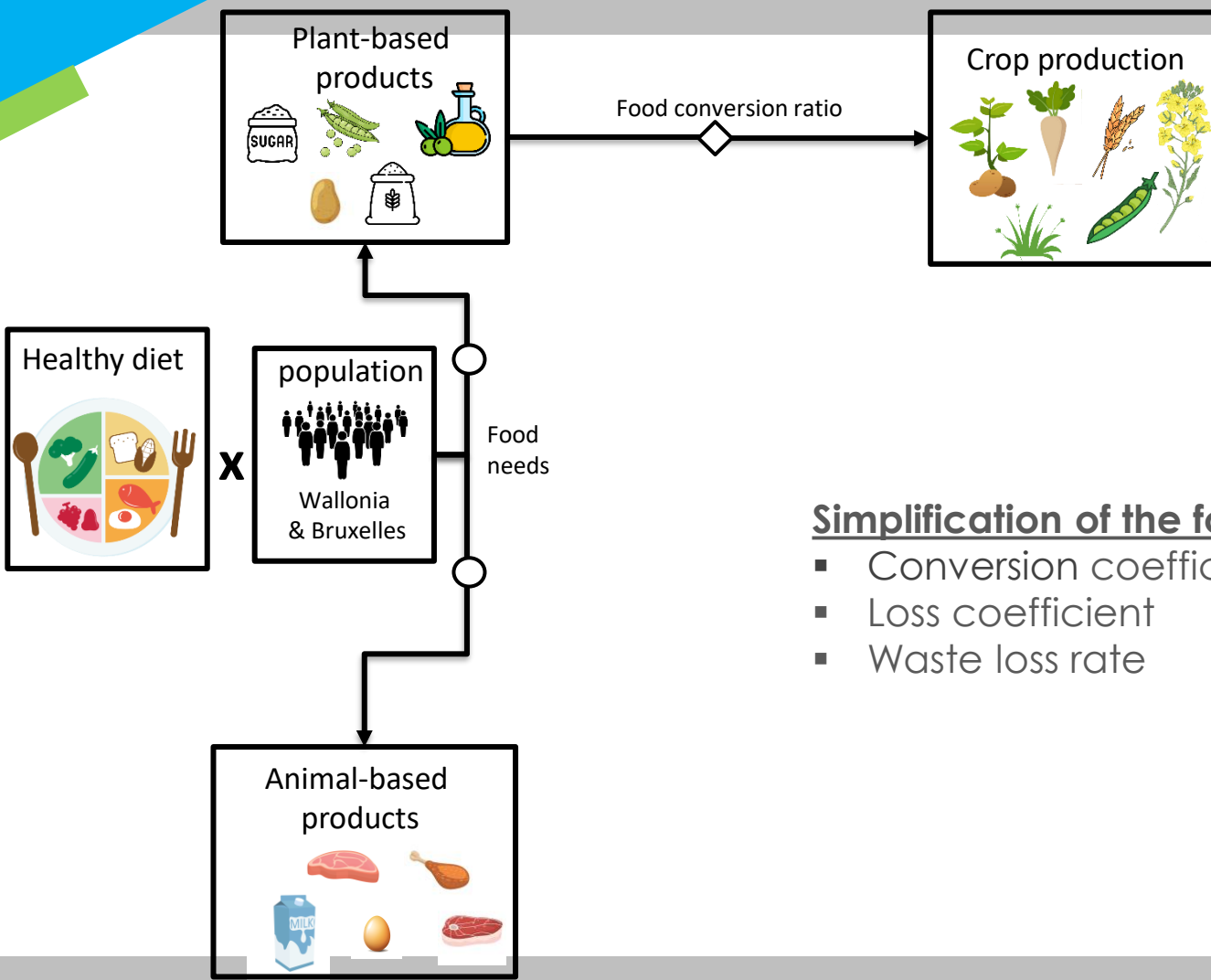
We decided to start from the plate...



... We selected diets that :

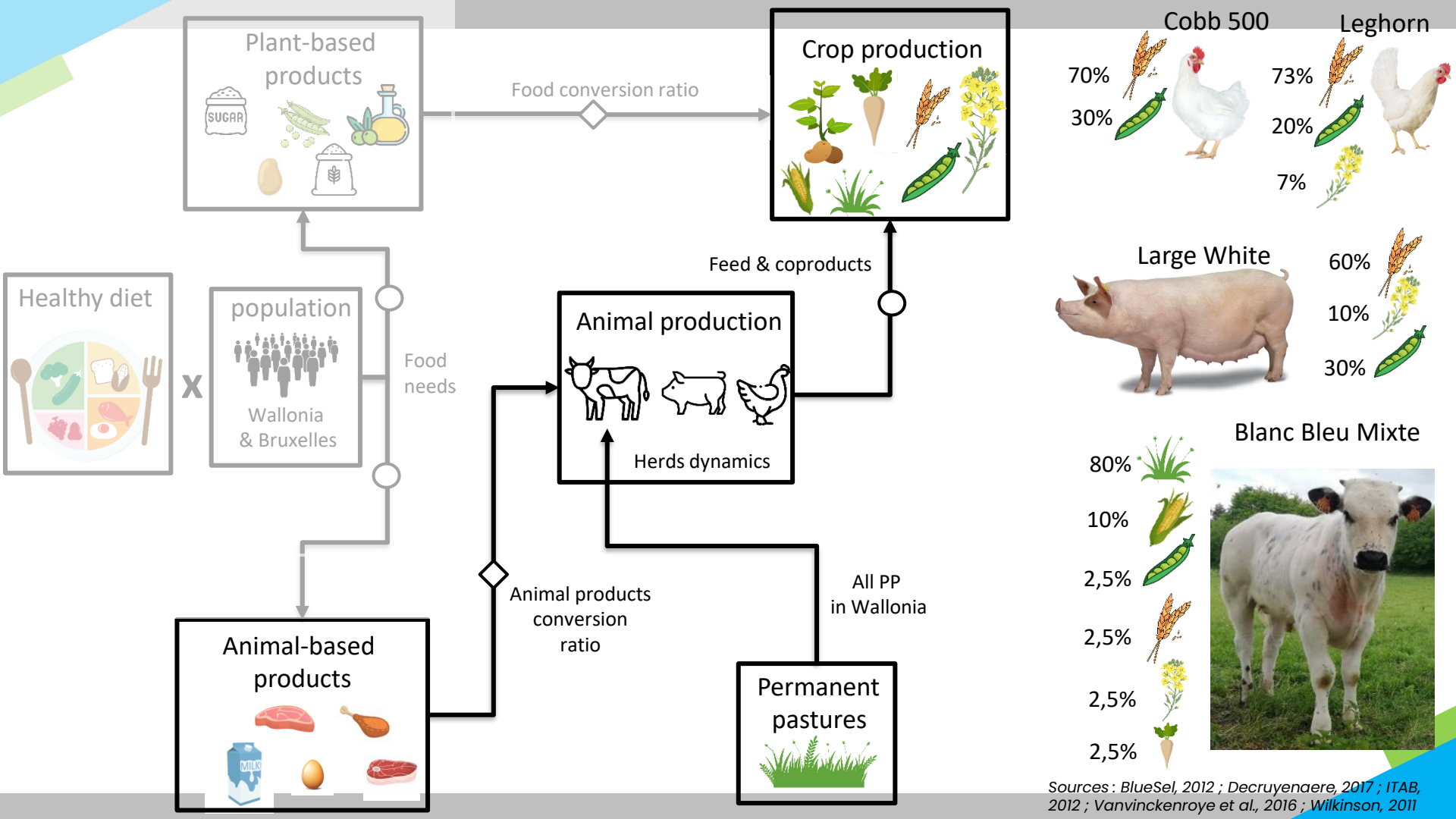
- are healthy
- are environmental-friendly

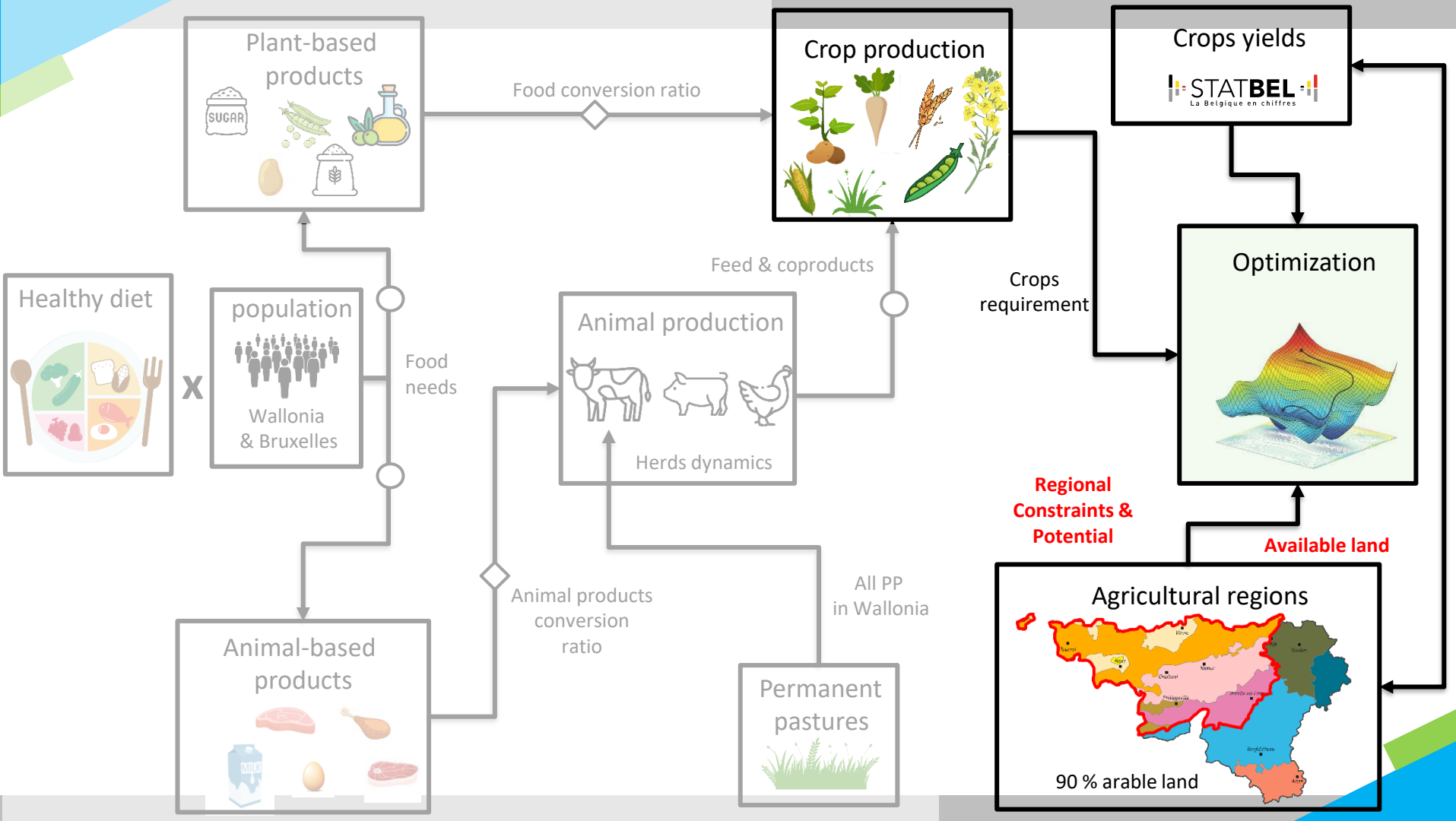




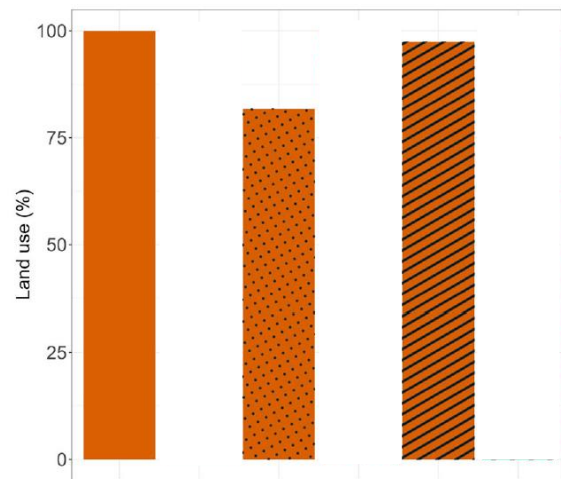
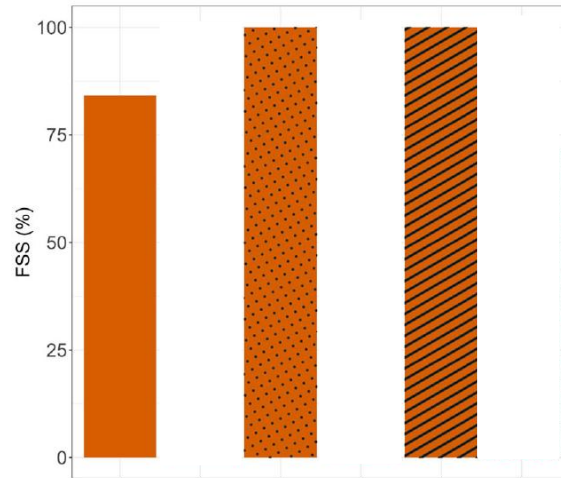
Simplification of the food system :

- Conversion coefficient
- Loss coefficient
- Waste loss rate

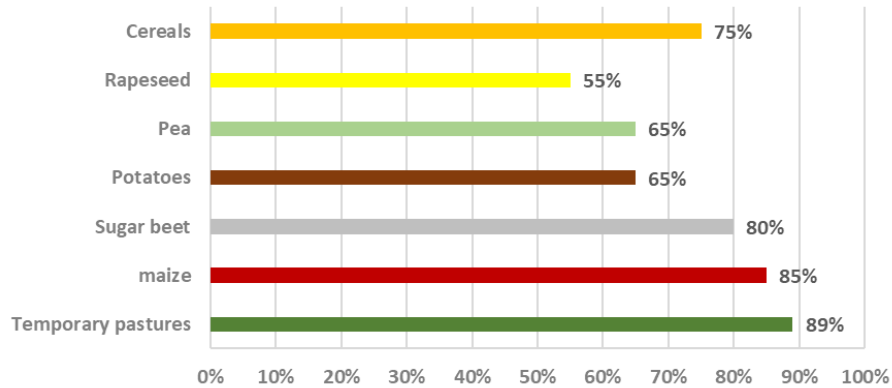




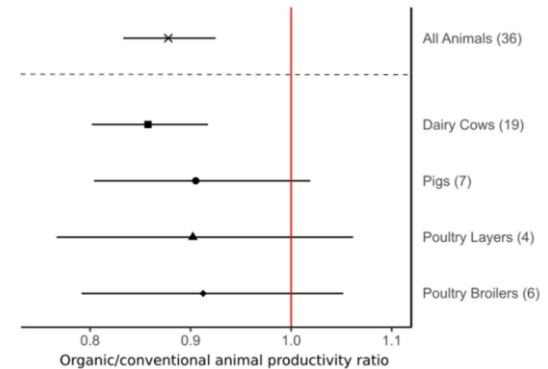
Food self-sufficiency



What if we go full « Organic » ?

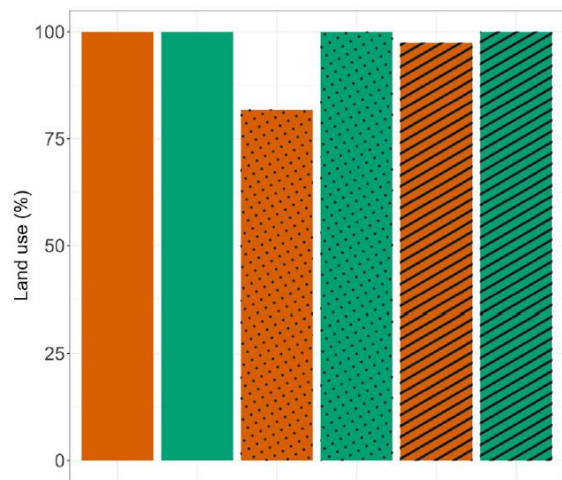
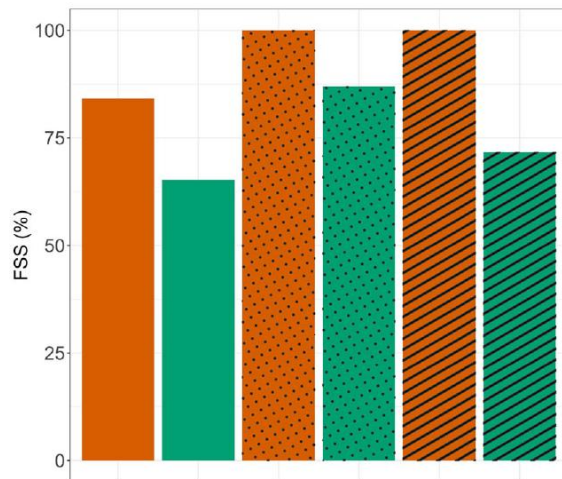


Sources : Poux & Aubert, 2018 ; Ponisio et al., 2015



Source : Gaudaré et al., 2021

Food self-sufficiency



scenario

- CURRENT-conventional
- CURRENT-organic
- EAT-LANCET-conventional
- EAT-LANCET-organic
- TYFA-conventional
- TYFA-organic

scenario

- CURRENT-conventional
- CURRENT-organic
- EAT-LANCET-conventional
- EAT-LANCET-organic
- TYFA-conventional
- TYFA-organic

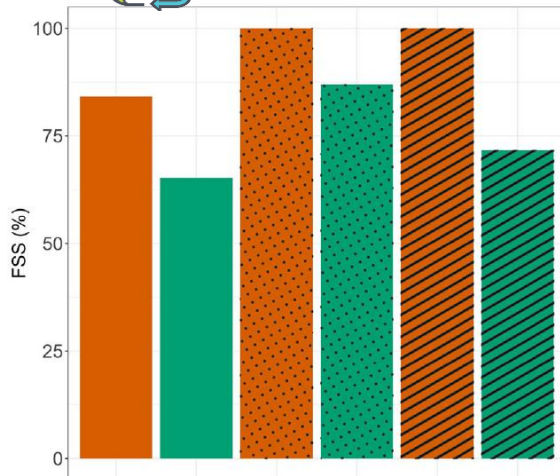
What if we waste less ?



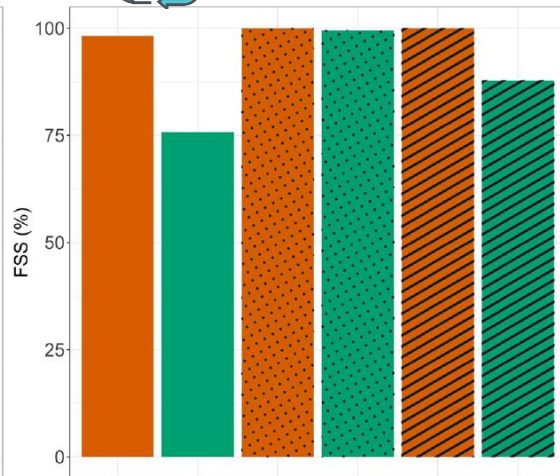
Food self-sufficiency



30% waste

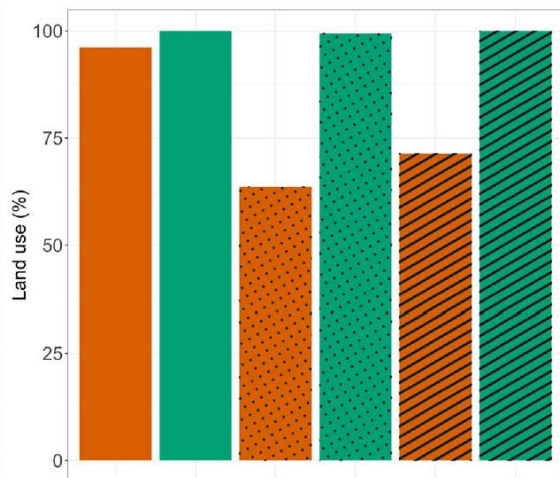
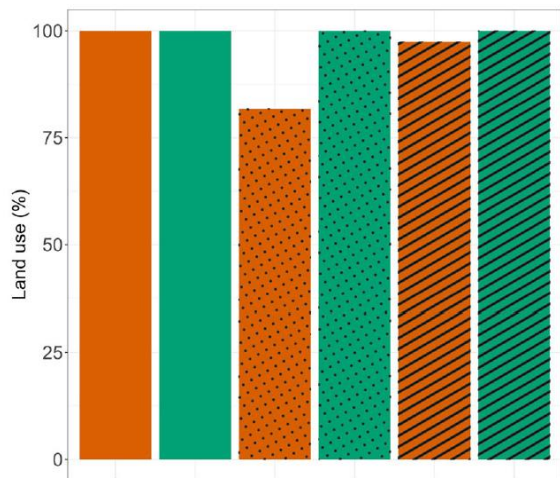


10% waste



scenario

- CURRENT-conventional
- CURRENT-organic
- EAT-LANCET-conventional
- EAT-LANCET-organic
- TYFA-conventional
- TYFA-organic

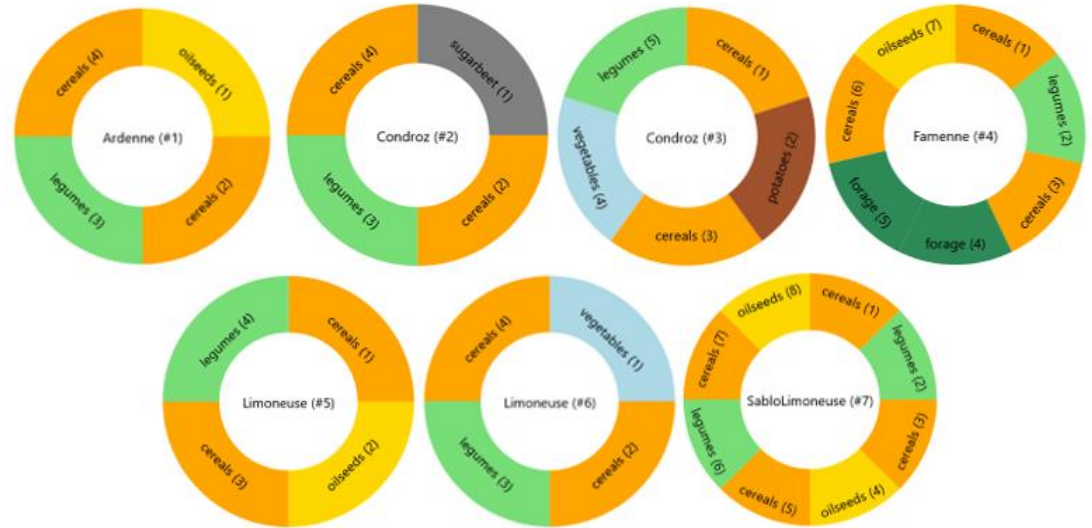


scenario

- CURRENT-conventional
- CURRENT-organic
- EAT-LANCET-conventional
- EAT-LANCET-organic
- TYFA-conventional
- TYFA-organic

The algorithm was coupled with **MILP approach** and adapted to :

- Account for return time of each crop
- Exclusion of specific crop sequences
- Aligning specificities of agronomic territory with specific crop needs





EcoFoodSystem



Reference rotation



ICLS rotation



Vegan rotation





Robustness over Efficiency



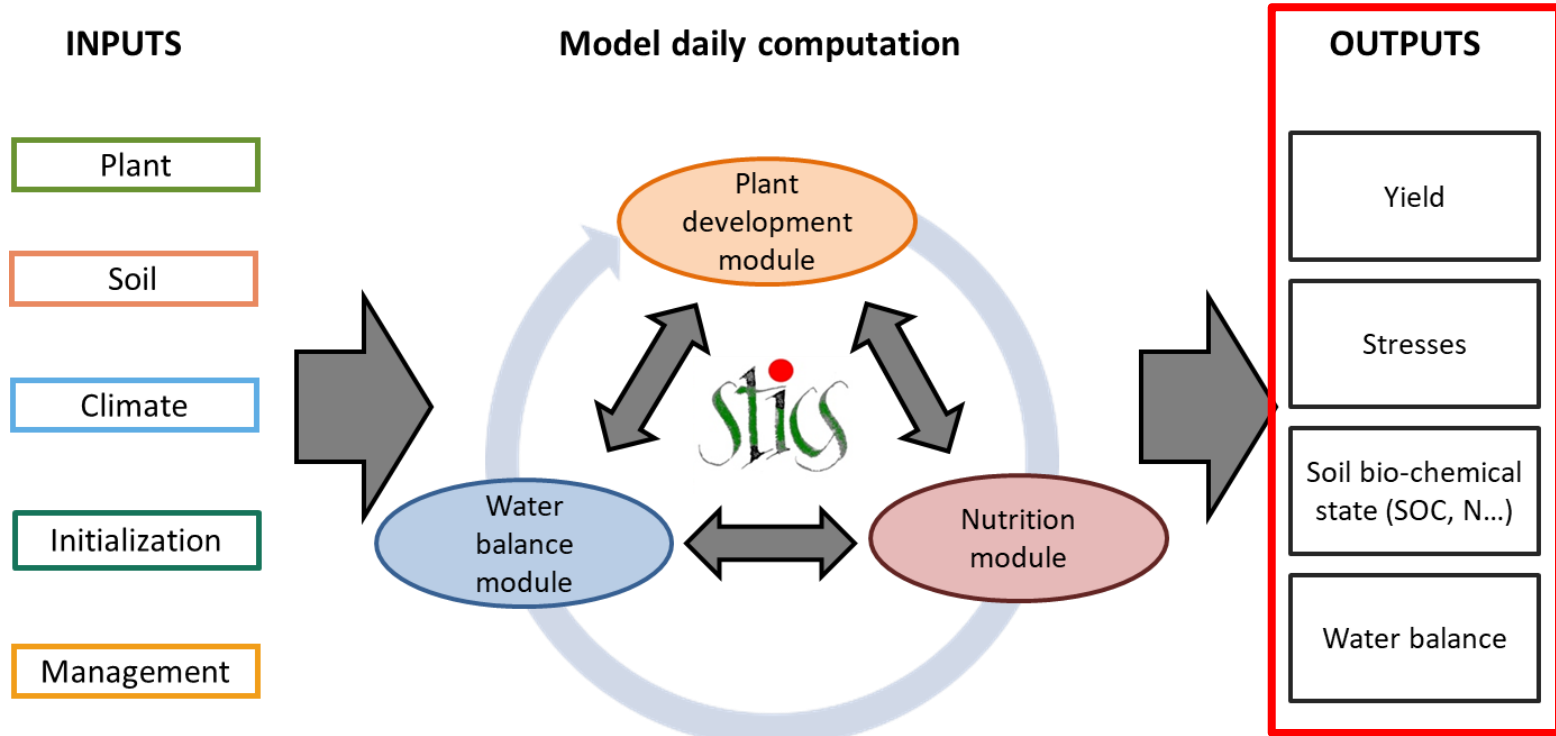
*« When a measure becomes a target,
it ceases to be a good measure »*

[Goodhart's law]



Soil crop modelling

→ Ecosystem Services (ESS)

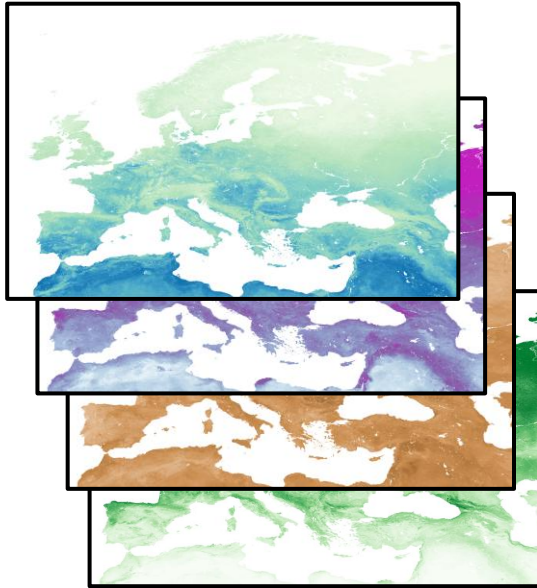


Sets of differential equation reproducing the behavior of Agroecosystems

A modelling framework



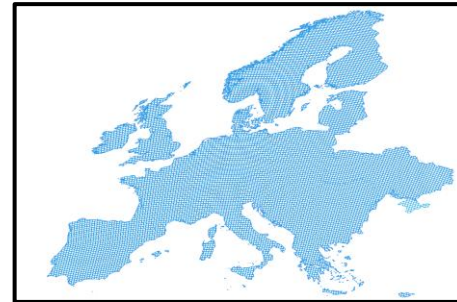
+2 millions soils profiles



5 soil layers
7 descriptors per layer

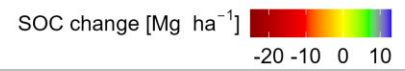
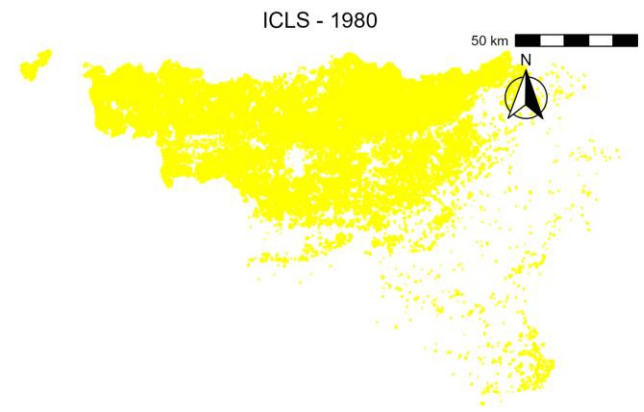
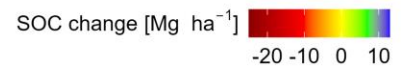
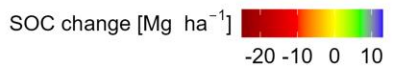
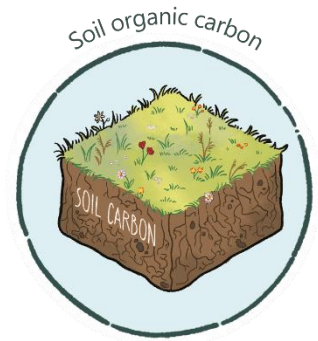
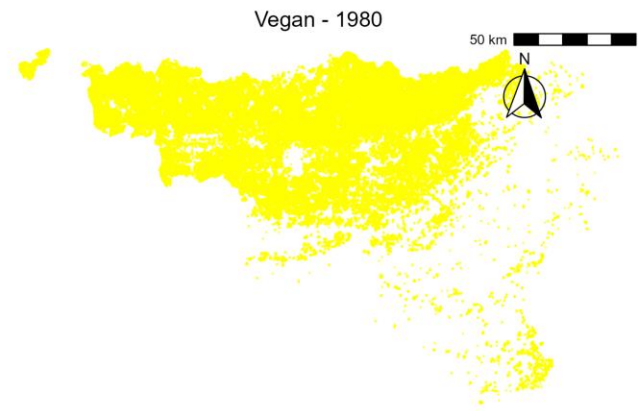
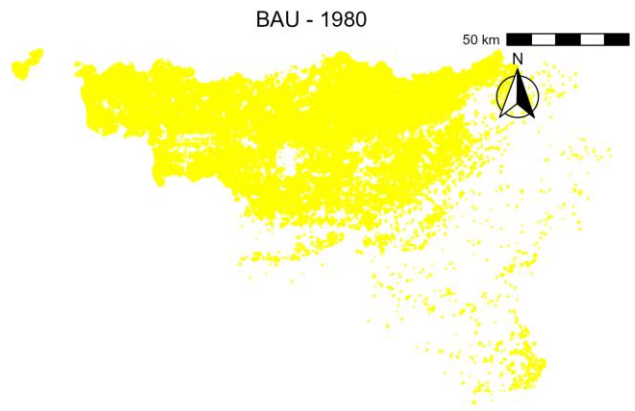


10.206 climatic tiles

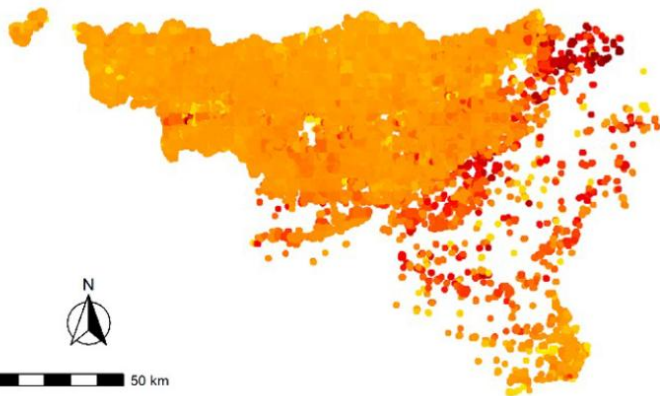


Historic records (Agri4cast)
Future projections (RCP scenarios)

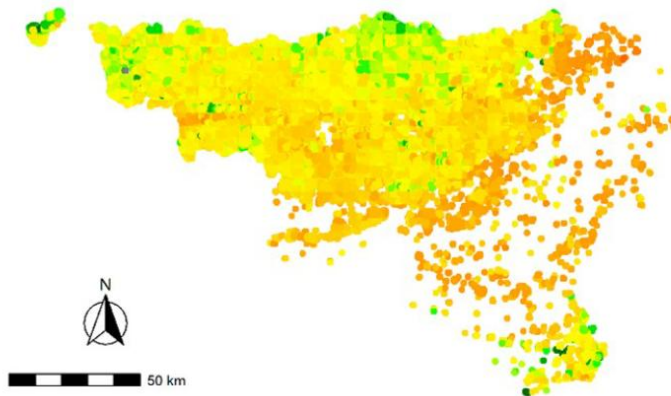




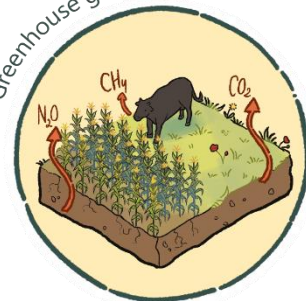
Business-as-usual



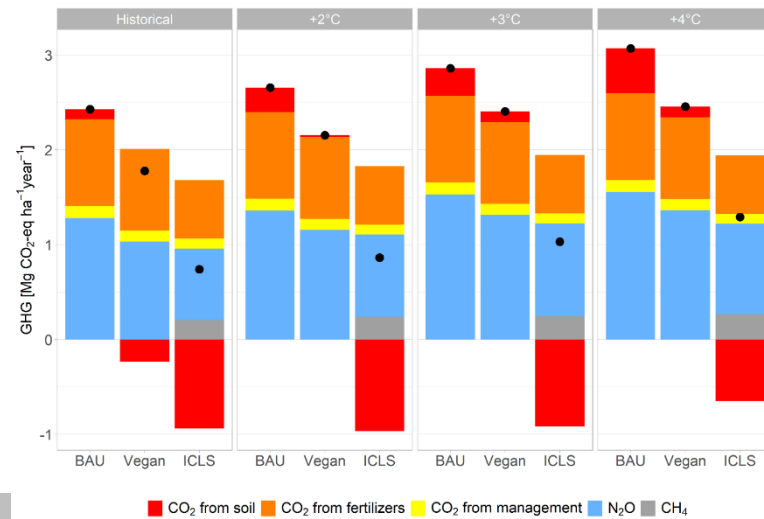
ICLS

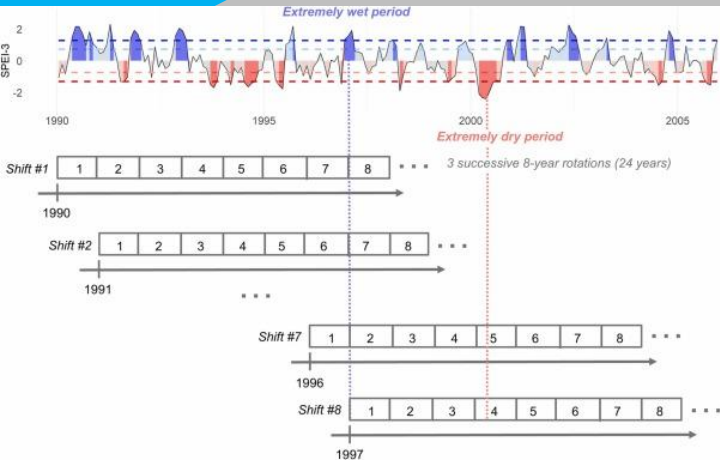


Greenhouse gas emissions

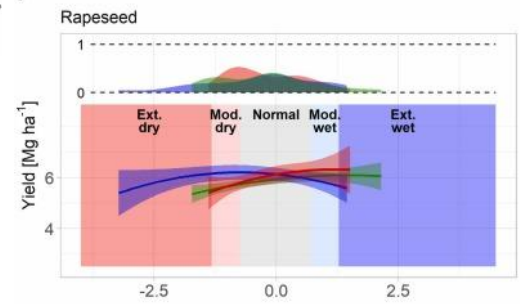


GHG budget [$\text{Mg CO}_2\text{-eq ha}^{-1}\text{year}^{-1}$]

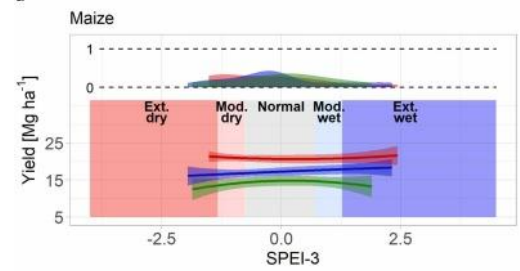




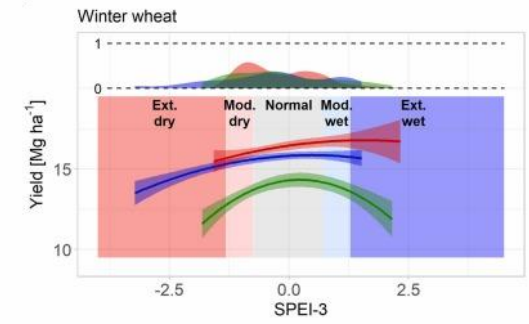
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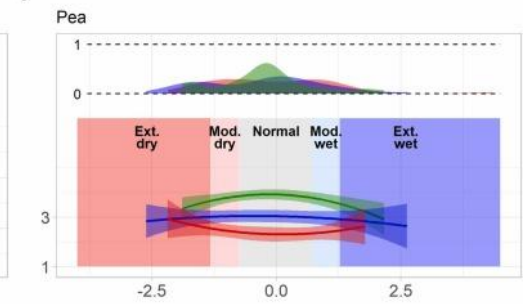
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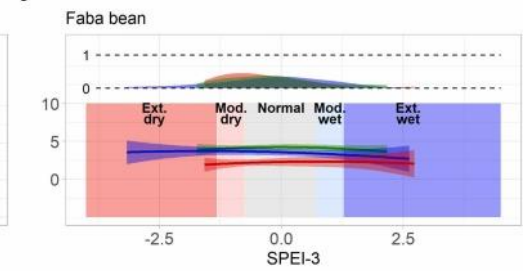
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c

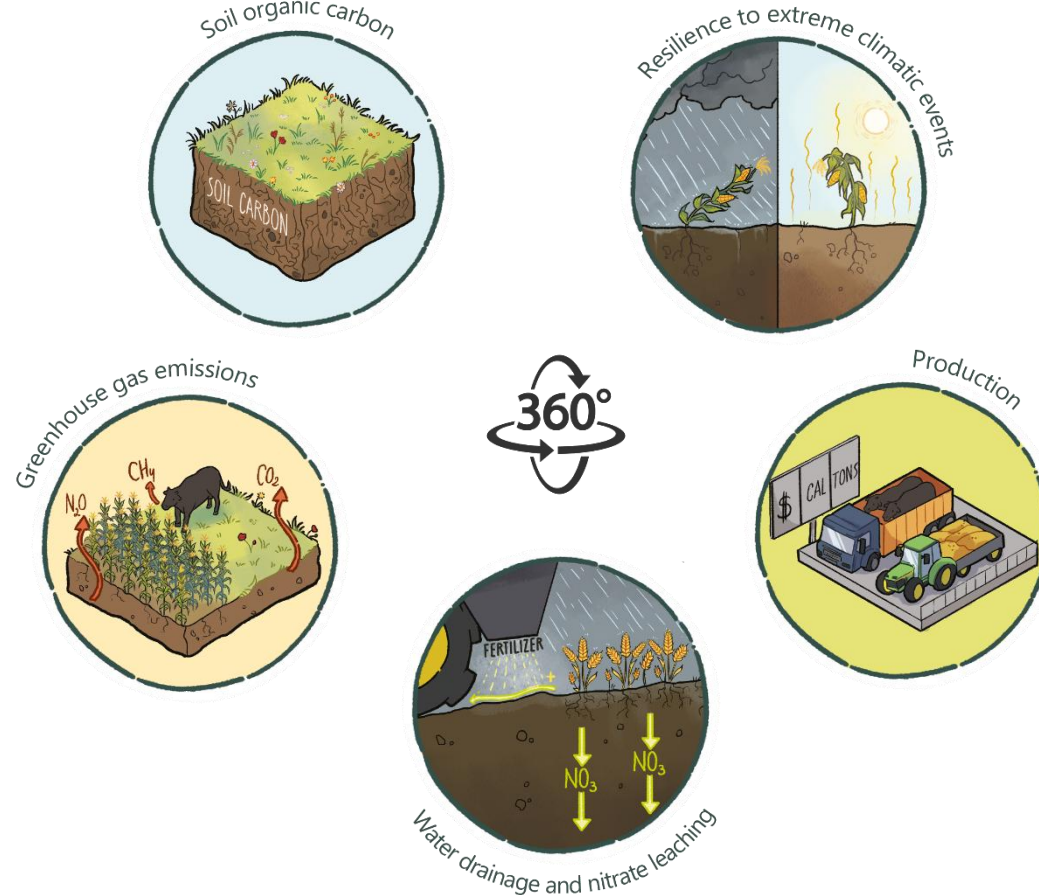


e

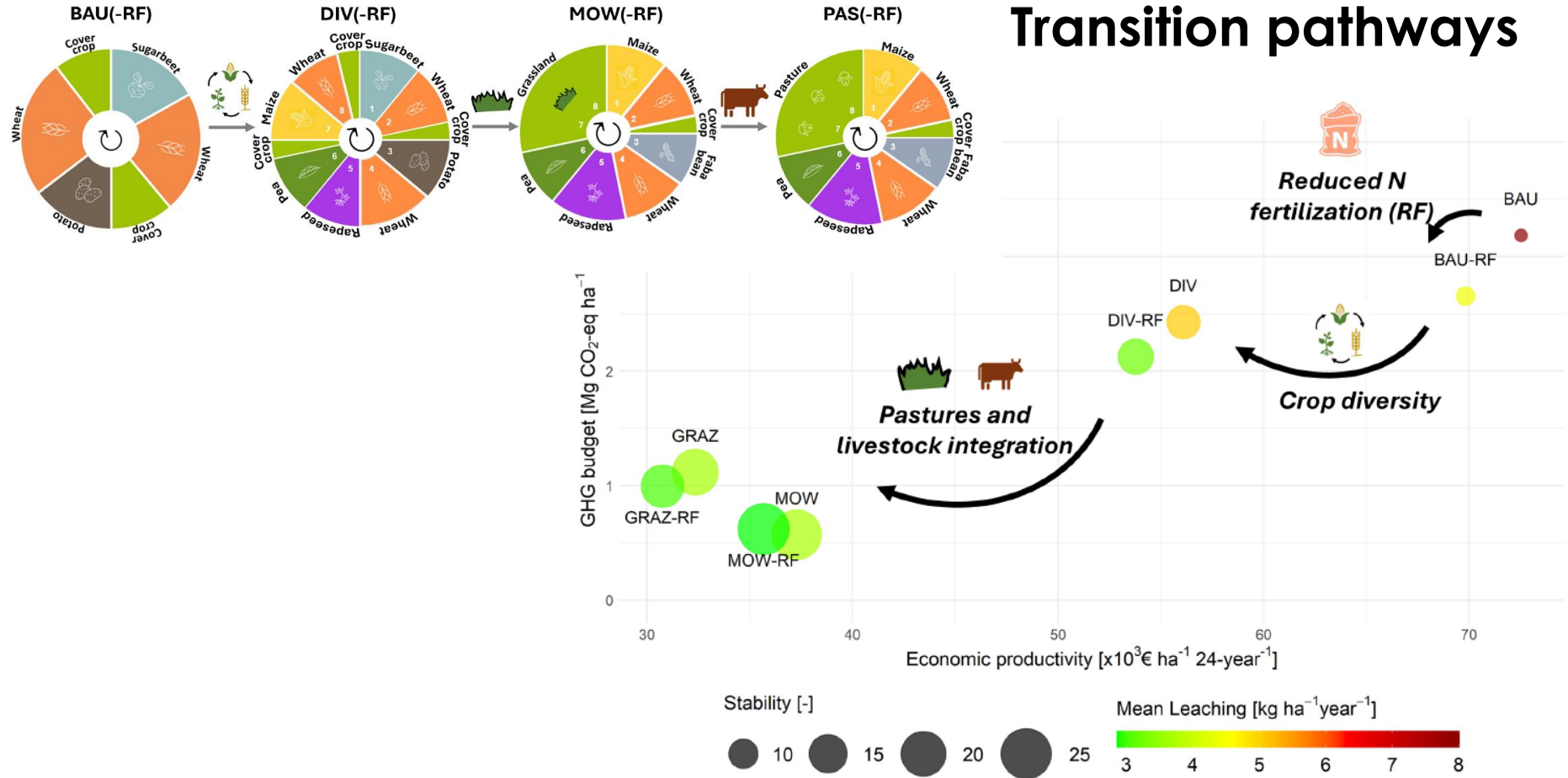


— 1980-2010 — 2040-2070 (RCP8.5) — 2070-2100 (RCP8.5)

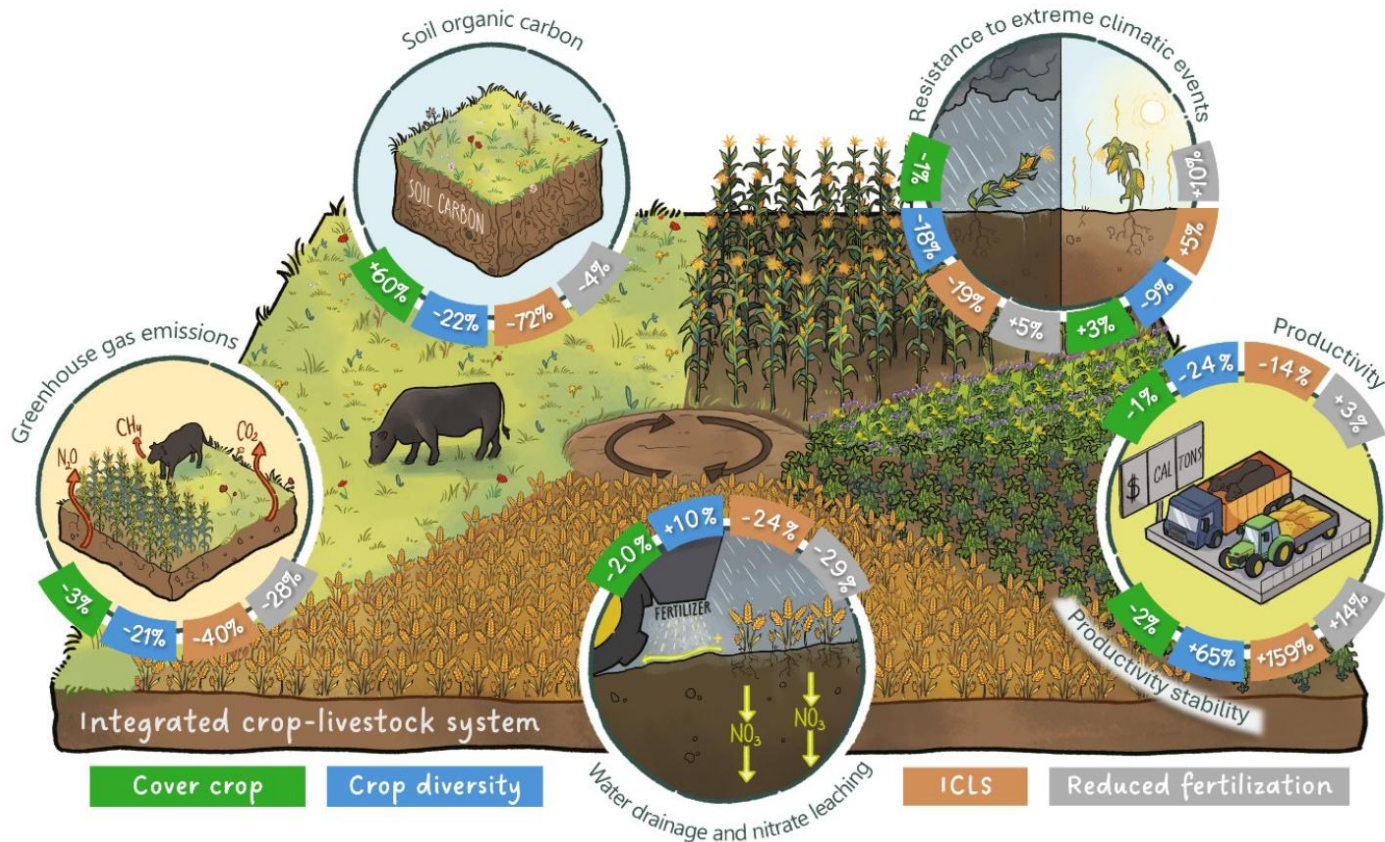
Bringing multi-performance into the game



Transition pathways



Bringing multi-performance into the game



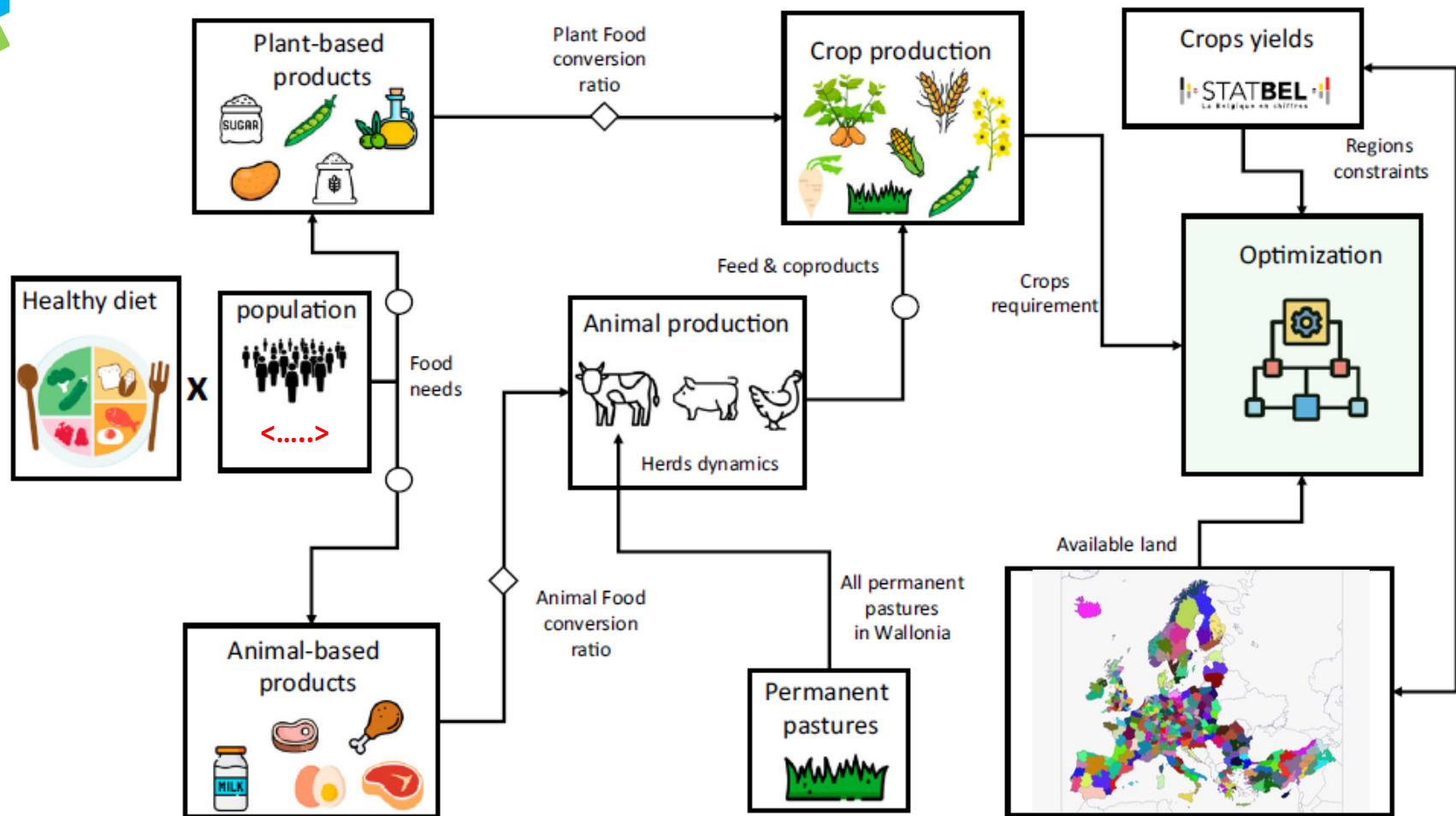


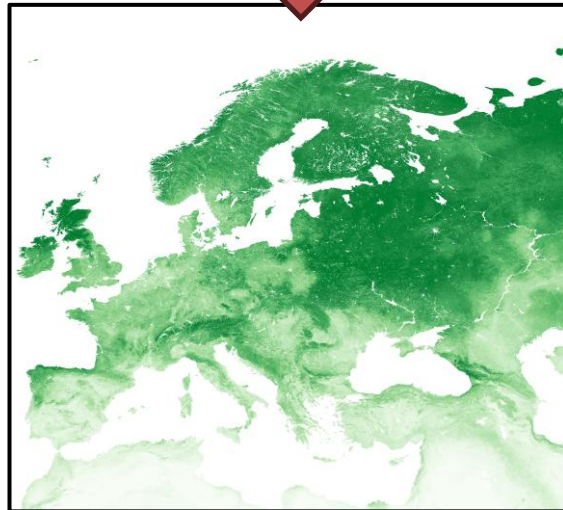
[Insert EU country
name here]



**Redesigning
<.....> agriculture
in a nutshell**







[iAMP-FP]



[FADN]



[HRL]



[LUCAS]



Conclusions

TAKE HOME MESSAGES

Take home messages

- Soil-crop model are powerful tools to **assess climate change impacts on ESS**
- Digital tools are efficient means to support the design of **future-proof, resilient and sustainable CS** to guide the **agroecological transition**
- We need to develop **robust cropping system** – i.e. under-optimal system when considering one metric – that **are multiperformant**
- We need to **reconsider what really matters**, i.e. food-oriented, healthy and environmental friendly cropping system !
- **? How can we help CAP and how can CAP help farmers in that direction, to avoid a locking of the systems in their current state ?**

Thanks for your attention

? QUESTIONS ?