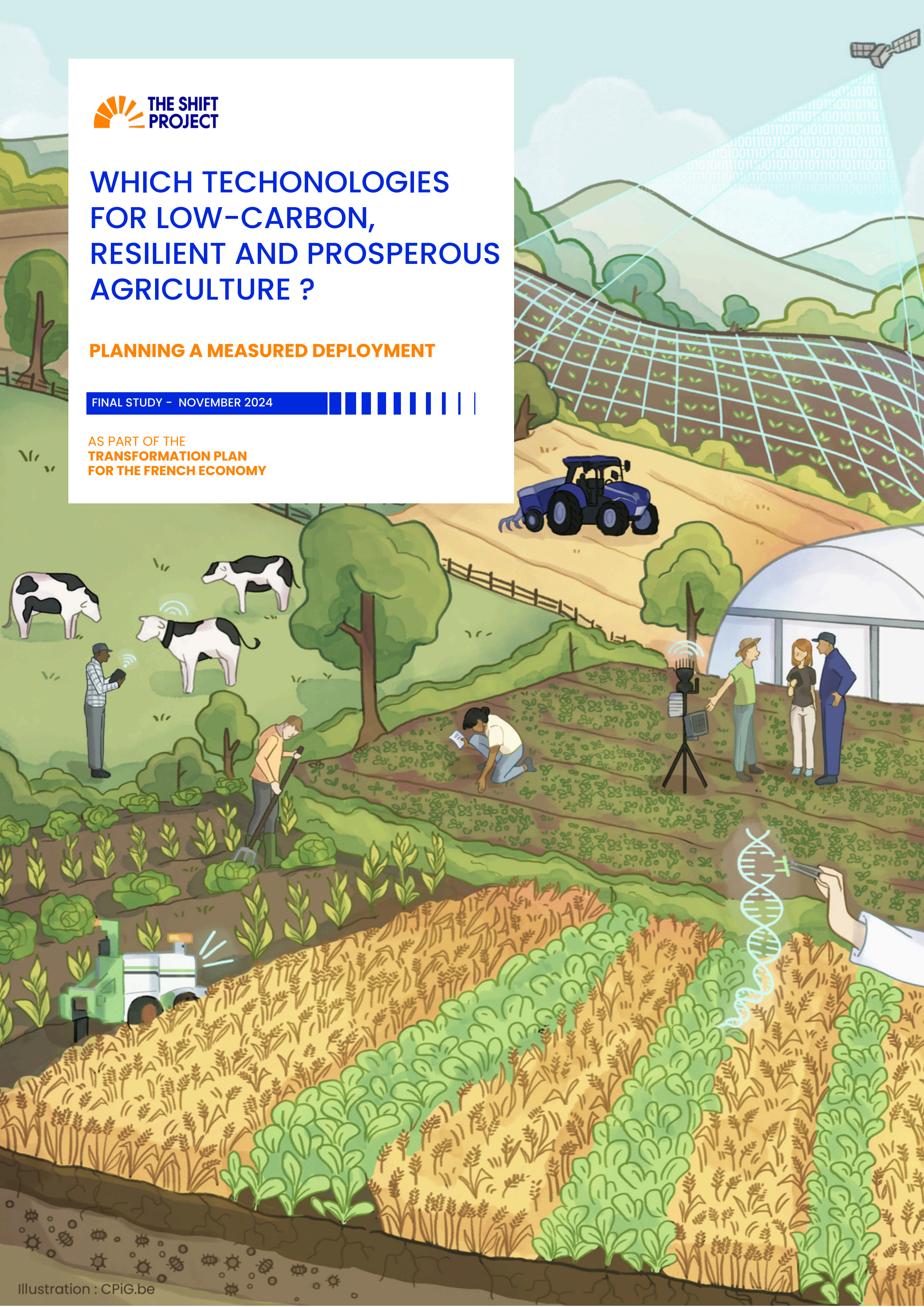
THE SHIFT PROJECT

WHICH TECHONOLOGIES FOR LOW-CARBON, RESILIENT AND PROSPEROUS AGRICULTURE ?

PLANNING A MEASURED DEPLOYMENT

FINAL STUDY - NOVEMBER 2024

AS PART OF THE
TRANSFORMATION PLAN
FOR THE FRENCH ECONOMY



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Foreword

For the past 14 years, **The Shift Project** has been working to shed light on the decarbonization of numerous economic sectors: transport, construction, industry and digital technology. However, we have - for too long - neglected to take an interest in the living world and biomass. **This document, focusing on agricultural technologies, complements The Shift Project's work on the agricultural sector.**

The Shift Project seeks to explore pragmatic and secure avenues for the transformation of the economic sectors it studies. Very often, **sectors include technological levers in the trajectories they explore**. The agricultural sector is no exception. These levers, with their varying levels of maturity and deployment, can also conceal rebound effects that need to be correctly identified to guard against them.

In this note, we propose to take a step back from the capacity of technologies to support the agricultural sector in its transition. **This document begins by proposing a method for deciphering agricultural technologies**. **This chapter is fully in line with the report "Pour une agriculture bas carbone, résiliente et prospère**" (**"For a low-carbon, resilient and prosperous agriculture**"[1], not translated in English) published in parallel, in that technological levers are sometimes proposed or at least mentioned. These methodological elements are exemplified through several technological case studies, chosen to cover a fairly broad spectrum of issues. We invite agricultural players (production, consulting, financing, etc.) to draw inspiration from them to explore technological trajectories for agricultural systems in their area, and to support their development in an enlightened way.

For the sake of readability and report length, not all the agricultural technologies studied will be detailed in the same way. Interested readers are invited to delve into the appendices to discover the technological case studies considered in this work. The aim of this report is to provide methodological elements that will help to shed light on the role of technological innovation in the transformation of the agricultural sector.

The report is divided into four distinct sections.

The first section offers a broad mapping of technological responses to the challenges of decarbonizing and adapting agriculture. To our knowledge, this overview is the first exercise of its kind.

In the second part of the report, we take a step back to identify the first obstacles to be overcome (dependencies, barriers, etc.) with regard to the possible deployment of agricultural technologies.

The third section proposes a methodology for deciphering technologies in terms of their ability to support a transition in the agricultural sector, identifying in particular their areas of relevance and the problems to be avoided. With a 360° vision, matrices of issues and levers are compiled to show the diversity of questions linked to the landing of agricultural technologies on farms. Typical farmer profiles are invoked to project the chosen technological responses into more concrete frameworks. The aim is by no means to put farmers in boxes, but rather to discuss the fit between agricultural technologies and the reality of farming systems in all their diversity.

The final section of this note invites us to think more broadly about the conditions for implementing agricultural technologies.

[1] Report "For a low-carbon, resilient and prosperous agriculture", The Shift Project, November 2024

About the Shift Project think tank

The Shift Project is a think-tank working towards a carbon-free economy. **A non-profit association under the French law of 1901**, its mission is to enlighten and influence the debate on energy and climate transition in Europe.

The Shift Project forms working groups around the most decisive issues of the transition, produces robust, quantified analyses of these issues, and develops rigorous, innovative proposals. It conducts lobbying campaigns to promote the recommendations of its working groups to political and economic decision-makers. It also organizes events to encourage discussion between stakeholders, and builds partnerships with professional and academic organizations in France and abroad.

The Shift Project was founded in 2010 by a number of business personalities with experience in both the voluntary and public sectors. It is supported by several major French and European companies, as well as public bodies, business associations and, since 2020, SMEs and individuals.

Since its inception, **The Shift Project has initiated over 50 research projects**, participated in the emergence of international events and organized several hundred symposia, forums, workshops and conferences. It has been able to significantly influence a number of public debates and political decisions important to the energy transition, both in France and within the European Union.

The Shift Project's ambition is to **mobilize companies, public authorities and intermediary bodies on the risks and opportunities for transformation arising from the "double carbon constraint"** of climate change on the one hand, and energy supply tensions on the other. Its approach is marked by a particular analytical prism, based on the conviction that energy is a key factor in development: consequently, the risks induced by climate change, intimately linked to energy use, involve a particular systemic and transdisciplinary complexity. Climate-energy issues are crucial to the future of humankind, and we need to integrate this dimension into our social model as quickly as possible.

It is backed by a network of tens of **thousands of volunteers** grouped together in an association under the law of 1901, the **Shifters**, created in 2014 to provide voluntary support to the Shift Project. Initially conceived as a structure to welcome anyone wishing to help the Shift with research, relay or support work, the Shifters are carrying out more and more independent work, but always with one objective: to contribute effectively to the exit from fossil fuels on a French and European scale**.**

Editorial Committee

The authors

Corentin Leroux, Leader of the “Agricultural Technologies” working group, Aspexit

Corentin Leroux trained as an agronomist. After a PhD in a private company around the processing of spatial data in agriculture, he set up his company Aspexit[2] in 2019 to support players in the agricultural world in the use of digital tools. Corentin writes popularization dossiers on themes combining agronomy, digital technologies, climate and energy. With Alexandre Touraine, he launched a collaborative platform - Wiki Agri Tech[3] - in 2024 to identify digital tools that can be used in agriculture. Corentin worked for The Shift Project as part of the regional project “Towards low-carbon regional economies”[4] on the Agro-Industry part and as part of the Agriculture project with this report on agricultural technologies. Corentin has also been heavily involved in the Shifters volunteer association since 2019.

Proofreaders

Céline Corpel, Cheffe de projet Agriculture, The Shift Project
Corentin Biardeau-Noyers, Ingénieur projet Agriculture, The Shift Project
Laure Le Quéré, Ingénieur projet experte, The Shift Project
Thomas Robert, Chargé de projet Agriculture, The Shift Project
Clémence Vorreux, Coordinatrice Agriculture, The Shift Project

The project also received communications support from Emma Stokking and Corentin Grange.

• Thanks

Weekly meetings of 1h30 took place over the period December 2023 - June 2024. All participants are not named here for reasons of confidentiality. Flash work sessions (face-to-face workshops, videoconferences, telephone calls) also took place in parallel with other players in the sector.

The Shift Project and Corentin Leroux would like to thank all the participants for the richness of their exchanges and the time they volunteered on a weekly basis to carry out this work.

Nota bene: the interpretations, positions and recommendations contained in this interim report cannot be attributed to either the contributors or the reviewers listed below. The contents of this report are the sole responsibility of The Shift Project.

[2] Aspexit website, https://www.aspexit.com/prestations-agriculture-et-numerique/
[3] WAT website, The participatory platform of 1552 Digital Tools for Farmers, https://www.wiki-agri-tech.com/
[4] Report “Towards Low-Carbon Regional Economies”, The Shift Project, September 2024, https://theshiftproject.org/article/verb-rapport-final/

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List of abbreviations

CO_2eq	CO_2 equivalent
GHG	Greenhouse Gases
GPS	Global Positioning System
LCA	Life Cycle Analysis
MAS	Marker-assisted selection
NGT	New Genetic Techniques
OF	Organic farming
OGM	Genetically Modified Organism
R&D	Research and Development
RTK	Real Time Kinematic
UV	Ultraviolet

THE SHIFT PROJECT

WHICH TECHNOLOGIES
FOR LOW-CARBON, RESILIENTE AND PROSPEROUS AGRICULTURE ?

A GREAT DIVERSITY OF AGRICULTURAL TECHNOLOGIES

- Not all technologies are comparable (in terms of maturity, deployment, adoption, etc.)
- Not all agricultural sectors are equipped at the same level

FIRST POINTS OF ATTENTION

- Risks of dependency and technological lock-in
- Technologies have an environmental footprint
- Technologies are not neutral, they influence the nature of uses

THERE IS A NEED FOR A METHOD TO ANALYZE AGRICULTURAL TECHNOLOGIES

The assessment must be **systematic** (for each technology, each particular case, each given application, etc.) and **exhaustive** (taking into account direct impacts and indirect and systemic impacts).

1 MAPPING OF ISSUES AND LEVERS FOR ACTION

- Evaluation of technological relationships, dependencies and synergies between technologies
- 360° issues of technology deployment : agronomic, technical, regulatory, financial, etc.
- Levers for action to exploit strengths and opportunities, and limit weaknesses and threats of deployment

2 PROJECTION OF TECHNOLOGIES ON FARMS

- Adequacy of technology with the agricultural system: structure and size of the farm, location of the farm, agricultural practices, regulations and technical supervision
- Use of typical farmer profiles to show the diversity of technological trajectories

THINKING ABOUT THE CONDITIONS FOR IMPLEMENTING AGRICULTURAL TECHNOLOGIES

- Cultivate heterogeneity by equipping all agricultural systems and not seeking standardization
- Adopt a principle of sobriety (individual, collective, structural) for agricultural technologies
- Adopt a culture of the precautionary principle to limit risks (infrastructural, physical, organizational, socio-economic flows, etc.)
- Think multi-scale by subscribing to local dynamics and trajectories and questioning the issues of plots – farm – sectors – territories
- Couple innovation systems (technological, agronomic, organizational, etc.)

What do we mean by agricultural technology ?

What is technology? **It would be risky to propose a single definition, since the notion depends so much on disciplines, contexts and uses**. In fact, it is directly linked to users. The term “technology” has often taken precedence over “technique”. Initially presented as a “discourse on techniques”, technology has come to evoke techniques that are often modern and complex. Technology is now often used in connection with the lexical field of innovation. So it's not uncommon to hear talk of new technologies, or even technologies of the future.

It's important to remember, however, that **innovation is not necessarily technological**[5]. Innovations can take many different forms: product innovations, process innovations, organizational innovations, marketing innovations... Although it should be accepted that an innovation is the landing or democratization of an invention in the field, we will use the term innovation in a relatively broad sense, thus overlapping with both the notions of innovation and invention.

There has often been talk of including the notion of agricultural practices within the scope of this work. To avoid procrastination and lengthy discussions, it was assumed that, with rare exceptions, **agricultural technologies were not decarbonizing or adaptive as such, but that they were there to accompany agricultural practices which were**. Agricultural practices are therefore not considered here as agricultural technologies. These agricultural practices are addressed more broadly in the Shift Project's report “For a low-carbon, resilient and prosperous agriculture”.

We strongly emphasize that this note focuses on technological innovations and not on all the many possible innovations in the agricultural sector. We are aware that agronomic innovations (relay-cropping, direct seeding under cover, crop and companion plant associations, insertion of agroforestry systems, etc.) and organizational innovations (supply circuits, pooling of tools via collective organizations, etc.) are all possible openings towards agro-ecological transitions. Technological innovations can support these “non-technological” innovations through innovation coupling, a subject we will return to later in this report.

For the purposes of this report, we have adopted a broad definition of agricultural technologies. They will be considered as a **set of modern techniques, more or less complex, in relation to already existing technologies**. We do not oppose sophisticated technologies to the sophisticated use of less complex technologies - each of which may have its place in a variety of agricultural trajectories. Exchanges around technologies must consider not only the technology as a technique in the traditional sense of the term, but also the way in which the technology is used, in the sense that the technology must be integrated into an agricultural production process.

Between the “Agriculture 2025” report (Bournigal et al., 2015) and the triptych now regularly heard from the mouth of President Macron “Digital, Genetics, Robotics”[6], **the perimeter of agricultural technologies is**

[5] OECD (2018). Oslo Manual. https://www.oecd.org/en/publications/2018/10/oslo-manual-2018_g1g9373b.html

[6] Speech by the President of the Republic on the occasion of the presentation of the France 2030 Plan, https://www.elysee.fr/emmanuel-macron/2021/10/12/presentation-du-plan-france-2030

very broad. We have deliberately limited it to technologies linked to climate change mitigation and adaptation (more on this later).

Funding for AgriTech and Biotech technologies[7] in the form of priority research equipment projects (PEPR - French Acronym) and calls for expressions of interest as part of the France 2030 plan, as well as funding for European projects (Horizon Europe), is far from negligible. Many of these technologies require lengthy research and substantial investment to reach maturity. **In the current context of budget constraints, it is therefore important to fully identify the issues they raise, in order to make informed choices and define appropriate public policies**.

A quick perusal of several French and European agricultural reports and plans (CAP National Strategic Plan, Farm to Fork Strategy of the European Green Deal, the Role of Artificial Intelligence in the Green Deal, the National Federation of Agricultural Workers' Unions' orientation report on the climate challenge, etc.) shows that the majority of them mention, to a greater or lesser extent, the use of technologies in agriculture's energy-climate transition. **It has to be said, however, that these references are often very vague**. Indeed, technologies are sometimes mentioned, at rather coarse levels of granularity, and are often embedded in more general innovation terminology. **The ability of these technologies to support the agricultural transition is generally accepted, without any particular demonstration, even though the diversity of agricultural technologies is dizzying and they are all far from being at the same level of maturity**. Even if we can't expect these framework documents to provide a detailed description of technological innovations, this lack of clarity gives rise to a techno-solutionist vision that does little to weigh up the risks that may arise from uninformed choices.

[7] Understand here agricultural technologies (Agritech) and biotechnologies (Biotech)

A panorama of technological innovations in agriculture

But first of all, what are we talking about? Mapping the existing ecosystem allows us to see the ecosystem as a whole, to create links between technologies, to identify what's missing, orphaned or forgotten, and to avoid reinventing the wheel. This mapping can be more or less detailed, depending on the degree of specialization required. We offer an initial overview in this section of the report. The panorama of this report is deliberately broad, to show a varied range of technologies.

1. Technology mapping methodology

The panorama could have been constructed in many different ways. Although we drew inspiration from Life Cycle Assessment (LCA) approaches or recent carbon labeling methodologies (Carbon Agri, Cap2er...), **we preferred to use a matrix representing a rough classification of agricultural production itineraries on the x-axis, and a breakdown of decarbonization and climate change adaptation issues on the y-axis (see Tables 1 and 2).** The farm itinerary axis is broad enough not to exclude any particular commodity or cropping system, and fine enough to accommodate agricultural technologies. The y-axis shows three macro-categories of issue: (1) limiting emissions of the main greenhouse gases from the agricultural system (N_2O, CH_4, CO_2), (2) storing and limiting the destocking of CO_2 in soils, and (3) adapting to climate disruption in the broadest sense. The adaptation category could certainly have been redrawn, but the ramifications would certainly have been very (too) numerous.

Two matrices have been produced, one for crop production and another for animal production, as we have considered agricultural technologies to be closer to each other within these two major production categories than between them.

Agricultural technological innovations are displayed in two main ways: either at the crossroads between an entity of a farming itinerary and a mitigation or adaptation issue, or straddling a long portion of the itinerary - always for the same mitigation/adaptation issue. It is important to understand that agricultural technologies are part of dynamic farming systems, with farming operations that follow one another, and that it is sometimes difficult to imagine the action of an agricultural technology at just one point on the spectrum. This is the case, for example, with biotechnologies or conventional breeding, which, by offering seeds that are more or less improved and adapted to the local environment, have a cascading impact on all the agricultural activities in the itinerary (because they will be more or less early, will require more or less water over a given period, more or less weeding, will be more or less prone to attacks by bio-aggressors...).

Once again, we remind you that the perimeter of the technologies invoked here stops at the farm gate. Technologies downstream of the farm (agri-food industries, distribution, consumers, etc.) are not considered here. We insist on the strong interactions between farming practices and agricultural technologies. **In the interests of intellectual honesty, we must accept that the majority of agricultural technologies are not decarbonizing or adaptive as such. Rather, they are there to accompany farming practices which are.** Agricultural technologies on Figures 1 and 2 have a link with the energy-climate transition of agriculture, whether from a mitigation or adaptation perspective. These links may be direct or implicit, and sometimes indirect or even at the limit of the issues at stake. Certain environmental and agronomic monitoring technologies, for example, are relevant for generating knowledge (which may or may not be integrated into agronomic models), justifying the implementation of a farming practice (from the point of view of obligations to achieve results), or serving to compare practices applied on a territorial scale in order to help all farms in a territory to progress (*nudge* or other).

Further details on the methodology used to build the technology panorama are available in the Appendix.

Agricultural technologies linked to the energy theme (methanization, small-scale wind power, agrivoltaism, decarbonization of mineral fertilizers, etc.) were not considered in the scope of this work. They will be dealt with in other Shift Project studies. Agrivoltaism is only mentioned in terms of its ability to protect agricultural production from the effects of climate change (shading, limiting water stress, etc.).

The scope of agricultural technologies stops at the farm gate. The Shift Project's position on a national trajectory for agribusiness has not yet been defined. It will be in 2026. Alongside this note on agricultural technologies, the Shift Project reaffirms its position on the agricultural sector (see the Shift Project's Agriculture report).

It is obviously difficult to focus on an energy-climate exercise to talk about a living sector like agriculture. As far as possible, we'll be looking at resources (water, plant protection products, etc.) from the angle of the double carbon constraint, i.e. the combination of climate disruption and depleting energy resources, with the use of water or plant protection products requiring energy in their use or manufacture.

Technology matrix for crop production

<table>
<tr><th></th><th>Sowing and Planting</th><th>Avoiding competition from other plants</th><th>Feeding the plant and the soil</th><th>Protecting and caring for the plant</th><th>Harvesting and post-harvesting</th></tr>
<tr><td rowspan="2">Adaptation to climate change</td><td colspan="5">Genetic selection (including NGT, Mutagenesis, conventional selection, introduction of biological heterogeneous material, etc.), Selection based on new criteria (inter- and intra-specific resistance contrasts, resilience to water stress, etc.), RTK geopositioning for specific crop schemes (inter- and intra-specific associated crops), Parametric/index insurance, Modeling of climate changes and future production areas, Production in a controlled and automated environment (greenhouses and others), Satellite monitoring of agroecological infrastructures (agroforestry systems, honey strips, ponds, etc.)</td></tr>
<tr><td>Crop rotation simulators, digital tools to help choose cover crops (particularly associated crops including legumes) and crop systems</td><td></td><td>Scoring of agricultural practices, Precision Irrigation (connected meters, semi-automated water balance, etc.)</td><td>Biostimulants & Mycelial Networks, Biocontrol, Agrivoltaism, Integrated Crop Management Modeling Tools, Crowdsourcing of New Emerging Diseases</td><td></td></tr>
<tr><td>Sequester and limit the release of CO_2</td><td>Satellite monitoring (intermediate crops, agroecological infrastructures, etc.), agricultural equipment to support the implementation of decarbonizing practices (sowing under cover, intermediate crops, etc.)..</td><td>Selective weeding (thermal, electric, UV, etc.), Non-selective weeding applied precisely</td><td>Genetics & Root Exudates, Biostimulants & Mycelial Networks, Biochar, Soil Activators, Carbon Traceability and Certification, Satellite Monitoring of Plant Cover and Nitrogen Residue Restitutions</td><td></td><td></td></tr>
<tr><td rowspan="2">Limit CO_2 emissions</td><td colspan="5">Organization and planning of agricultural worksites (fleet management and telemetry, serious eco-driving game and others...), Light robotics and light agricultural equipment, Improving the efficiency of agricultural equipment and machine adjustment assistance tools (Tractor diagnostics, Torque-consumption, Optimizing tire inflation, Tractor-tool suitability, range of use), Electric motorization</td></tr>
<tr><td></td><td></td><td></td><td></td><td>Optimization of harvesting rounds and logistics in general (by satellite imagery, telemetry, etc.), Logistics and storage optimization tools (environmental sensors, silo sensors, etc.), Environmental sensors and silo sensors to reduce losses</td></tr>
</table>

Limit N_2O emissions	Genetic selection with optimal use of nitrogen or genetic selection of plants (mainly legumes, research efforts on cereals) that fix nitrogen (including NGT, Mutagenesis, Conventional selection, etc.)				
			Variable rate application, Nitrification inhibitors, Nano fertilizers, Integral nitrogen control models, Spectrometry of organic fertilizers, Decision support tool for spreading application windows, Improved spreading agricultural equipment, Biostimulants		Specific agricultural equipment for sorting and enhancing the value of legumes grown in association (optical sorter in silos)

Table 1: Technological innovations in plant production

Technology matrix for animal production

	Reproduction management	Feeding and watering	Condition and cleanliness of buildings	Protecting and caring for animals	Collection and slaughtering
Adaptation to climate change	Genetic selection of rustic breeds and/or varieties adapted to stresses induced by climate change (e.g. thermo-tolerant), Aquaculture ponds in a controlled and automated environment (aquaponics, etc.), Parametric/index insurance				
		Tools to help choose grassland covers, tools to help harvest fodder (weather), tools to measure the nutritional value of fodder (MAT, proteins, etc.)		Real-time monitoring of animal heat stress	
Sequester and limit CO_2 release **Limit CO_2 emissions**		Satellite monitoring of the state of meadows	Sensors and tools for monitoring on-site energy consumption		
Limit CH_4 emissions	CAP2ER diagnosis (French carbon diagnosis for animal production), Genetic selection (including conventional selection [low methane, etc.], NGT, etc.)				
	Calving collar to reduce the age of renewal	Enteric CH4 inhibitors (food additives, chemical inhibitors, ionophores, etc.), Ration modulation (precision feeding), Eco food formulation, Vaccine against methanogenic microorganisms, Robotic pills for internal monitoring of methanogenesis, Methane masks, Holobiont genetics, Reduction of the share of unsaturated lipids in rations		Tools for monitoring the health status of livestock (impact of this parameter on productivity and methane emissions)	
Limit N_2O emissions					
		Food ecoformulation, Ration modulation (precision feeding), Multiphase feeding, increased use of amino acids in biphase feeding,	Covering of pits, Direct evacuation of slurry, Air washing, Misting		

		use of extruded raw materials in formulation			

Table 2: Technological innovations in animal production

2. Significant heterogeneity of agricultural technologies across agricultural systems

The diversity of the technological innovations on offer can be surprising. On the one hand, **this abundance testifies to the fact that there are (and certainly will be) no miracle technologies in agriculture, given the diversity of agricultural systems**. Rather, a multitude of technological responses will support the transformation of the agricultural sector. On the other hand, **this panorama shows that many technologies do exist** - albeit in varying states of maturity - and that some of them are already active in the agricultural field, in experimentation or in operational conditions.

The distribution of agricultural technologies on the panorama also reveals which parts of the spectrum are being widely investigated (subject to technological innovation), and which are a little more neglected. The absence of technologies at certain intersections of agricultural itineraries and transition issues is not always surprising. For example, the relationship between avoiding competition between plants and carbon storage (or limiting its removal) is not easy to find.

Complementing these technological orientations is the question of the scale of work or impact of these technologies. The majority of existing agricultural technologies tend to be applied at farm or even plot level. Larger scales such as value chains, watersheds, territories or landscapes are often missing from this technological panorama, and sometimes indicate a real lack of hindsight on the part of innovation players. While some decarbonization and adaptation levers can undoubtedly be activated on a farm-by-farm basis, it is clear that **some systemic changes go far beyond the scale of the individual company**. Integrated technologies across an entire value chain can be a way of supporting profound change, at the risk, of course, of subjecting the value chain to new constraints or bottlenecks that need to be anticipated. These technologies are not easy to implement, however, as the needs of the players involved with farmers can be very varied.

Particularly in crop production:

Since the CO_2 footprint is mainly due to the fuel used by machinery in the field, it's hardly surprising that the majority of technological innovations here focus on agri-equipment. Tools to aid machine adjustment and tractor diagnostics (torque-consumption, tractor-implement suitability, range of use) can help reduce consumption. Fuel savings can also be achieved through smaller machine sizes (e.g. lightweight robotics) and the use of all kinds of technologies to optimize travel and touring. Substituting fossil fuels to power machines also plays an important role. We'll just mention it here in the context of electric motors. Energy issues (methanization, energy crops, etc.) are not covered in this report.

The impact of nitrogen fertilization on agriculture's greenhouse gas footprint is now well documented. **Agricultural technologies have largely focused on reducing emissions linked to fertilization**. These include technologies for optimizing nitrogen inputs to increase the efficiency of nitrogen use, through more precise recommendations of nitrogen requirements or more sophisticated agri-equipment (intra-parcel modulation, burying of inputs, etc.). Other technologies focus on directly reducing soil nitrogen emissions (nitrification inhibitors, nano-fertilizers, etc.). The latter can also be enhanced by breeding varieties that make better use of available nitrogen.

Agricultural technologies to increase CO2 storage or limit its release are ultimately quite present in the panorama (in number) even if their use is perhaps a little more limited compared to other technological innovations. Here we find firstly the tools for monitoring carbon storage practices (by satellite imagery or other) such as the establishment of plant covers (by checking whether they are established or not - or by measuring levels of biomass returned) or no-till (even if the practice is not unanimous in terms of carbon release). These agricultural technologies then intervene here under a logic of performance obligations (by using technology to prove or justify the implementation of agroecological practices). We will also place here the agro-equipment that allows these carbon storage practices to be scaled up. Also included are all the technologies linked to inputs to the soil with more or less direct effects on sequestration: soil activators, development of mycelial networks (in particular mycorrhizal) by biostimulation, the input of biochar (by pyrolysis of plant biomass). Also present are all the technologies linked to carbon certification (carbon credits, sector bonuses) which can use digital tools for the collection or traceability of agricultural systems' data.

Some of the adaptation support technologies cover the entire agricultural itinerary, unlike mitigation technologies which are rather focused on one part of the itinerary (even if this could be subject to discussion for some technologies). This diffuse presence for certain technologies is explained by the fact that they are production systems in their own right (production technologies in controlled environments such as greenhouses [see one of the technological case studies discussed below]), that they have a cascading impact on the entire route once they are implemented (selection and genetic improvement tools can affect all subsequent cultivation operations), or that they can be used at any time in the production cycle (for example, classic or parametric climate insurance technologies[8]). Having defined only one major macro-category of adaptation to climate change, we have also positioned several other technologies linked to support for sowing (decision-making tools for crop rotation or varietal choice, particularly on intraspecific mixtures), all the tools linked to water management (precision irrigation, reuse of treated wastewater, etc.) and those for crop protection in the event of exacerbated climate change (biostimulation and biofortification to increase plant resistance, agrivoltaism to protect against the effects of heat stress, etc.).

More specifically in animal production:

The vast majority of agricultural technologies focus on reducing enteric methane emissions with the aim of reducing the footprint of polygastric production per tonne of food product (per live weight, per litre of milk, etc.). These technologies generally affect the diet, whether on the content (food additives considered anti-methanogenic, eco-formulation of processes or food supplies, share of unsaturated lipids in the ration) or on the quantity provided (modulation of the ration). Some technologies presented a little further upstream in the production process, such as calving collars or heat detection tools, can be used to reduce the age of first calving and optimise herd renewal rates, thus contributing overall to a reduction in the unit footprint of animal production.

Since genetics plays a significant role in the variability of methane emissions from animals, genetic selection technologies (e.g. low methane) are an option for reducing the footprint of livestock systems. However, reductions are expected in the medium term (from 2030)[9].

[8] https://www.aspexit.com/agricultural-weather-insurance-undergoing-reform/#Insurance_Digital_Index_or_Parametric_Insurance

[9] Report "For a low-carbon, resilient and prosperous agriculture", The Shift Project, November 2024

As discussed in the introduction, **we find here relatively few technologies adapted to mixed crop-livestock, grass-fed livestock or agro-pastoral livestock systems**. The biomass monitoring technologies or agroecological practices (agroecological infrastructures such as hedges or others, etc.) presented in the panorama of plant production can be adapted for grassland contexts or for forage biomass (assistance in choosing grassland covers, satellite monitoring of grassland conditions, index insurance technologies on grassland development, etc.).

Genetic selection technologies in the broad sense already discussed to support the adaptation of the agricultural sector are also adapted in an animal context (for example, selection of rustic and/or thermo-tolerant breeds, increase in genetic diversity). Some technologies for monitoring animal health conditions also make it possible to anticipate potential risks linked to climate change (monitoring of heat stress by camera, flow meters connected to water troughs, etc.).

3. Selection of technological innovations

The panorama of innovations presented in the previous section is too broad to cover them all in the context of this study. We prefer to choose technologies or packages of technologies here that allow us to highlight issues that seem relevant to us to discuss in the context of thinking about the role that technologies can play in the ecological transition.

We try to cover a broad sample of technologies so as to be able to discuss technologies adapted to plant and animal production, technologies considered to be "high tech" and "low tech", technologies used on the scale of an agricultural farm or in a broader logic of landscape, territory or sector, or even relatively solitary technologies as a counterweight to packages of technological solutions.

Some of the technologies chosen could appear contradictory to each other (for example, new genomic technologies and classic conventional selection). We rather consider that these tools are complementary. It is nevertheless clear that all these technologies are not deployed at the same level in the field. **Some technical and economic orientations (mixed crop-livestock, legumes, etc.) have not received the same attention as the others and are therefore not equipped in the same way.**

We have identified 8 different technological innovations here. Once again, not all of them are detailed with the same finesse in the rest of the report. We refer interested readers to the appendices. The main reason for choosing these technologies is presented below.

1. **Optimization of nitrogen supply [NI]**: to show a combination of technologies (Decision Support Tool [DST] for spreading application window, variable rate application, integral steering model, nitrogen form, etc.) on the nitrogen subject, the importance of which in terms of agricultural greenhouse gas (GHG) emissions is known.
2. **New genomic technologies [NGT]**: to fuel the debate on controversial technologies that offer promise for the development of new crops.
3. **Conventional selection [CS]**: to highlight various tools, some of which have been modernized and optimized with high-throughput molecular marking and genetic selection. This case study also allows us to discuss existing fractures in certain sectors neglected by classic conventional selection.
4. **Peasant agricultural equipment for mechanical weeding [PAE]**: to discuss sober and frugal technologies, as a counterweight to the current agricultural equipment sector.
5. **Electric robotics for selective weeding [ROB]**: it is difficult not to talk about agricultural robotics in view of current research trends (Great Robotics Challenge[10] in particular in France). This case study focuses on lightweight robotic tools powered by electrical energy.
6. **Optimization of animal feed [FEED]**: to show a combination of technologies (Ration modulation, Eco-formulations, Anti-Methanogens, etc.) on the subject of methane, the importance of which in terms of agricultural GHG emissions is known. This case study also allows us to question the place of animal production and meat consumption in France from a new angle.
7. **Collaborative digital solutions for pest management [DIG]**: to offer a technological reading by changing scale (landscape, territory) because agricultural technologies are often proposed at the farm scale. The values of mutual aid and sharing must be predominant in the transition.

[10] https://anr.fr/ProjetIA-23-GDRA-0001

8. **Controlled Environment Production [CEP]**: to discuss local production methods that are often less well-known to the general public and sometimes subject to controversy.

The following table presents the technologies using a reading grid to consider the transition of the agricultural sector. This table should not be seen as a grid for selecting technological case studies but rather as an initial descriptive proposal of these technologies.

Criteria	**Technologies (see nomenclature above)**							
	NI	NGT	CS	PAE	ROB	FEED	DIG	CEP
Dedicated to decarbonization	✓	×	×	-	-	✓	×	-
Dedicated to adaptation	×	✓	✓	✓	-	×	✓	✓
Controversial technology	×	✓	×	×	-	✓	×	×
Mature and deployable	✓	-	✓	-		✓	-	✓
Can cause breakages	×	✓	×	×	✓	×	×	×
Ability to have quantitative impact data	✓	×	×	✓	✓	✓	×	✓
With orphan themes	✓	✓	✓	×	×	×	×	✓
Considered low-tech	×	×	-	✓	×	×	✓	×

Tableau 3 : Catégorisation des innovations technologiques sélectionnées suivant un lot de critères.

Légende : ✓(Oui) ; × (Non) ; - (Mitigé)

First locks to be lifted

Viewpoints on technology, perhaps even more exacerbated in the agricultural sector, can be very divergent. The place of technology in agriculture, as in other sectors, is too rarely discussed, and **speeches lacking nuance ("pro-techno" versus "anti-techno") develop in a climate of tensions and oppositions that are harmful to a dynamic favorable to the peaceful transformation of the sector**. However, if each "camp" is convinced that its position is the right one, the reality is that the path of transition will most likely borrow from both, to allow the mobilization of technological innovation in favor of the agroecological transition without compromising the sector in ways that bring additional constraints and dependencies to a sector that already faces a lot. The reflection pursued within the framework of this working group does not aim to dissuade the deployment of technological solutions in agriculture. On the contrary, it invites us to define a framework that will ensure them an optimal role and place with regard to the objectives pursued, and a peaceful and safe development. We believe that general reading elements and methodological elements can calm discourses that often generate tensions and support sometimes ideological oppositions.

The transformation of the agricultural and agri-food system is urgent to respond to physical constraints as well as socio-economic challenges. If the technological path can offer solutions[11,12,13] it is nevertheless not the only one. Given the diversity of technological tools discussed in this report (limited by the scope of this work), this argument could seem simplistic in the sense that there should indeed be technologies in this panorama capable of supporting the transition of the sector. Nevertheless, all the resources deployed in technological directions (financing, regulation, human work, etc.) are supports or backing that will not be developed elsewhere. **It is therefore important to ensure that these resources are wisely directed so that they support all areas of solutions.**

There is no doubt that many agricultural technologies have indeed enabled significant developments for our societies. Agricultural yields have reached spectacular levels with the joint use of seeds of selected varieties, chemistry to reduce the impact of bioaggressors, inputs of mineral nitrogen fertilizers to feed the plant, or even agricultural equipment to optimize working time and efforts in the field. Agricultural technologies have helped to improve the working comfort of farmers with increasingly ergonomic and efficient agricultural equipment. In addition, the technological tools already widely deployed seek to improve the environmental impact of the practices they aim to support (increasing the efficiency of inputs, improving the productivity of agricultural equipment, etc.).

Nevertheless, the contributions of past years of agricultural technologies cannot be considered all things being equal given the physical constraints that the agricultural sector faces.

1. Multiple dependencies and technological lock-in possibilities

Agriculture is already largely dependent on fossil fuels, this is no longer in doubt[14]. Can we afford to develop technological proposals that do not contribute to freeing ourselves from systems already subject to fossil fuels? Two recent reports from the Shift Project remind us that European oil and gas supplies are at risk[15]. Will our technological choices be adapted to an agriculture that has successfully transformed itself and freed itself from its fossil fuel grip? Will they contribute to it? Even if it is true that we are experiencing more of a crisis of abundance than

[11] Bournigal et al., (2015). 30 projets pour une agriculture compétitive et respectueuse de l'environnement. #AgricultureInnovation2025.

[12] Inrae (2023). État des connaissances sur la contribution des technologies d'édition du génome à l'amélioration des plantes pour la transition agroécologique et l'adaptation au changement climatique

[13] Inria – Inrae (2022). Agriculture et Numérique. Tirer le meilleur du numérique pour contribuer à la transition vers des agricultures et des systèmes alimentaires durables.

[14] Harchaoui, S., and Chatzimpiros, P.(2018). Can Agriculture Balance Its Energy Consumption and Continue to Produce Food ? A Framework Assessing Energy Neutrality Applied to French Agriculture. Sustainability, 10

[15] The Shift Project (2021). Pétrole : quels risques pour les approvisionnements de l'Europe ? https://theshiftproject.org/article/nouveau-rapport-approvisionnement-petrolier-europe/
The Shift Project (2022). Gaz naturel : quels risques pour l'approvisionnement de l'UE ? https://theshiftproject.org/article/gaz-risques-approvisionnement-ue-rapport-shift-project/

a crisis of scarcity, this question is not insignificant. Thinking about resilient technologies in an agriculture that has successfully transformed itself calls for questioning the capacity of these technologies to remain relevant in a world with degraded conditions.

In this report, **we talk about technological innovations and even technological packages in agriculture**. Innovations first of all because many technologies are not yet widely disseminated on farms. This entry into fields or farm buildings is heterogeneous[16], depending on a multitude of historical, sociological, technical or even financial factors[17]. Let us also add that certain technologies may be adapted to certain situations but harmful in others (example of agrivoltaism). It is therefore important that the deployment methods are well thought out and supervised.

Our collective commitment to a particular technology (or technologies), sometimes at a relatively low level of maturity, guides us on a trajectory from which we cannot necessarily deviate (notions of technological lock-in[18,19,20] and path dependency[21]). While certain technologies can indeed support decarbonization and adaptation to climate change, others can, on the contrary, hinder certain agricultural routes because they contribute directly or indirectly to strengthening the dominant agricultural model. **By making certain agricultural routes dependent on technologies, new dependencies** (on a manufacturer, a tool supplier, or even a collection/storage organization) **are also likely to emerge[22]**.

Without going so far as to hinder agroecological routes, the use of agricultural technologies could lead to discussing the need to adapt certain routes to land technologies there (reorganization of crop systems to facilitate the passage of a robot, genetic selection to improve the shape of the udder with respect to robotic milking, etc.). **The question of whether the tool should adapt to agricultural practice or whether, on the contrary, the practice should adapt to the tool, remains open.**

Here then, the **concept of appropriate technology[23]**, with the double meaning of appropriation by the user who would be able to use or maintain the technology, and of appropriation of the technology to the use it will have, seems very appropriate to us.

Technological packages then because we must consider that **technologies are interdependent and intertwined**. Some technologies need other neighbors or cousins to function and deploy their full potential. The development of certain technologies involves the development of other intertwined technologies. We are talking here about the technologies themselves, but also about all the infrastructures on which they depend, infrastructures that must be deployed in a certain number of cases. For example, in retrospect, the widespread use of synthetic nitrogen fertilizers could only take off because there was, simultaneously, work on varietal selection to have crops that make the best use of this nitrogen, and phytosanitary solutions to respond to the effects of this maximization of nitrogen (straw shorteners for wheat to

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[16] Lowenberg-Deboer, James, and Bruce Erickson. 2019. "Setting the Record Straight on Precision Agriculture Adoption." Agronomy Journal 111(4): 1552–69

[17] Pathak, Hari Sharan, Philip Brown, and Talitha Best. 2019. "A Systematic Literature Review of the Factors Affecting the Precision Agriculture Adoption Process." Precision Agriculture 20(6): 1292–1316.

[18] Clapp, Jennifer, and Sarah Louise Ruder. 2020. "Precision Technologies for Agriculture: Digital Farming, Gene-Edited Crops, and the Politics of Sustainability." Global Environmental Politics 20(3): 49–69

[19] Académie des technologies (2023). Avis de l'académie des technologies sur les nouvelles technologies génomiques appliquées aux plantes.

[20] De Wit, M.M. (2021). Can agroecology and CRISPR mix? The politics of complementarity and moving toward technology sovereignty. Agriculture and Human Values.

[21] Carolan, 2020a. "Acting like an Algorithm: Digital Farming Platforms and the Trajectories They (Need Not) Lock-In." Agriculture and Human Values 37(4): 1041–53

[22] Schnebelin, Éléonore, et al.. 2021. "How Digitalisation Interacts with Ecologisation? Perspectives from Actors of the French Agricultural Innovation System." Journal of Rural Studies. https://linkinghub.elsevier.com/retrieve/pii/S0743016721002205.

[23] Atelier Paysan (2021). Reprendre la terre aux machines. Manifeste pour une autonomie paysanne et alimentaire

prevent lodging, and promote the absorption of nitrogen in the grains, for example). **These concepts of rebound effects[24] or technological stacking in the different sectors of the economy continue to be documented[25]. Agriculture is no exception.**

Given the time taken to develop and deploy technologies, **they must now necessarily be designed from the outset – by design – for agroecological routes**, in order to be compatible with the desired evolution of agricultural practices. Clearly, the **agricultural technologies deployed to date have focused on the logic of optimizing existing routes**: reducing inputs (water, phytosanitary products, energy, etc.), efficiency of agricultural equipment, optimization of routes. It is to be feared that these optimization logics will not be sufficient on their own to provide a long-term solution to the crises of the global food system. Even if it is not impossible that agricultural technologies will be dedicated to logics of substitution or redesign of agricultural routes, the examples remain fragile and sometimes more than theoretical.

2. Measuring the environmental impact of agricultural technologies

If energy-climate issues are beginning to take their place in the debate, the idea that agricultural technologies are central to the evolution of agricultural practices has quickly become established (mainly from the perspective of optimization, as mentioned above). However, **the environmental footprint of these technologies themselves is rarely mentioned, and very rarely measured or taken into account** (an issue that is not specific to the agricultural sector). It often seems to be considered that the impacts inherent in agricultural technologies are offset by the benefits they are supposed to bring to the sector. However, the material footprint of technologies - think of digital tools, agricultural equipment or even robotics - is beginning to be documented[26,27] - and can no longer be neglected.

How can we think of agricultural technologies in terms of mitigation and adaptation to climate change when it is not for these objectives that the technologies were initially developed? Methodological difficulties exist when it comes to attributing GHG reduction effects to a specific technology. If digital nitrogen fertilizer management tools have, for example, been developed to provide recommendations to the plot, can we really correctly assess an environmental gain associated with these technologies, all things being equal, when that is not necessarily their primary intention? How can we then be able to extract the unit effect of the technology with regard to the entire production process? It is of course possible to measure environmental gains (parsimonious data on effective reduction or adaptation are nevertheless not always available) but, even if the technology has helped to support the implementation of an agricultural practice, can we allocate all or part of the impact that this practice has managed to generate to it? It should be noted, however, that the environmental gains brought about by agricultural technologies can only be estimated in relation to a hypothetical counterfactual situation.

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[24] The Shift Project (2023). Planifier la décarbonation du système numérique en France.

[25] Fressoz (2024). Sans Transition. Une nouvelle histoire de l'énergie. Essais Ecocène.

[26] Pradel, M., et al. (2022). Comparative Life Cycle Assessment of intra-row and inter-row weeding practices using autonomous robot systems in French vineyards. Science of the Total Environmental, 838.

[27] Ademe (2022). Évaluation de l'impact environnemental du numérique en France et analyse prospective. Évaluation environnementale des équipements et infrastructures numériques.

To continue in the same vein, we could also **ask ourselves what would have happened if the technology had not been used or developed**. What is an agricultural itinerary with technological tools compared to? **The choice of the starting point or the reference** brings with it the relevance of using technological development. Is implementing complex technological innovations to improve or transform agricultural practices that could already be optimized a sufficient response (for example by deploying precise and targeted irrigation management tools before rethinking more water-efficient agricultural practices)? Agricultural technologies aimed at decarbonization only make sense when they are complementary to a dynamic in which measures to change agricultural practices, sobriety and efficiency have already been explored and activated. The gap to be filled between the initial state and the technological state is thus better characterized, and the relevance of deploying the technological tool can be correctly defined.

As long as an agricultural technology is considered relevant for the agricultural transition, it is important to **question its relevant level of deployment** to really provide the interest we give it. Some agricultural technologies may be so transformative that a small introduction already offers significant benefits. Others, on the contrary, will probably have to be pushed to the limit to show a differentiating advantage. Introducing these latest technologies then requires using them to the maximum to ensure that the initial investment is profitable.

3. A false sense of impartiality in agricultural technologies

Agricultural technologies are not neutral. To the argument of the knife generally brandished, it being understood that everything would depend on the way in which this knife is used, it must on the contrary be recalled that all technology is part of an already well-established socio-technical system. We cannot and should not say much about technological forms when they are extracted from their networks, practices, affects and discourses[28]. Technological devices are never simple independent objects; they are always relational in their essence. It is time to stop asking what these technologies are and instead to be interested in what they do, what they promote, what they imply and in which system they are inserted. **The actors who intervene in the technological ecosystem in agriculture must take responsibility** and keep in mind that they all have a role, at one time or another, in the landing of technologies on the agricultural field and, by extension, on the associated consequences and impacts, whether positive or negative[29].

Our vision of the world impacts the way we develop and shape agricultural technologies. These technologies embed the values, affects or even the representations of those who developed them. For example, measuring instruments or sensors measure, supervise or even evaluate what we see or have decided to see, even if we may not necessarily have the technological tools to measure what should have been measured. The agronomic models that we develop contribute to a simplification of the world around us and are directly linked to the way we represent it.

[28] Carolan, 2020. “Acting like an Algorithm: Digital Farming Platforms and the Trajectories They (Need Not) Lock-In.” Agriculture and Human Values 37(4): 1041–53

[29] Flandrin, L., and Verrax, F., (2019). Quelle éthique pour l’ingénieur ? Editions Charles Léopold Mayer. 260p.

We could go so far as to talk about **fractures of accuracy and precision**[30,31], because technologies are not always adapted or even designed for all agricultural routes. Some agricultural sectors are actually partly left out of agricultural technologies in the sense that they are not as equipped as others (mixed crop-livestock, legumes, organic farming, low-input systems, etc.), for financial or regulatory reasons or for issues related to the organization of sectors or outlets. Supporting diversified agricultural systems will require the mobilization of technologies in a balanced manner between agricultural sectors.

Technologies do not enter farms all things being equal. The adoption of technologies is a long and gradual process, sometimes involving back-and-forth[32], and which largely involves both farmers in the field and all local stakeholders (technicians, advisors, etc.). These are all non-technical themes that need to be addressed, between notions of identity at work and the relationship with one's work, the land, and animals, questions of work organization on the farm and the relationship with potential employees, or even issues surrounding new skills to be acquired and support for change to be implemented[33]. We will discuss this again in the description of technological innovations.

It is clear that agricultural technologies benefit from significant media noise. The dominant narratives use powerful images to shape society's perception of what is currently at stake[34]. The stories of shortages (energy, food, etc.) mainly deployed tend to be told in relation to the way in which resources are used, justifying all the more the use of technological adjustments. By supposedly making it possible to deal with the profound unpredictability of the climate, agricultural technologies are presented as life-saving and can contribute to casting doubt on the state and reliability of conventional and empirical knowledge on agriculture. **The propensity of our societies to want to control and simplify agricultural production by abstracting themselves from the complexity of living things sometimes leads us to favor the use of technology with a constant system rather than rethinking the system in light of the challenges that are imposed on it**[35]. The innovative farmer, keen on technology, is often celebrated and highlighted as an actor ahead of the curve in the media ecosystem. He is often opposed to his colleague who is more inclined to traditional practices and distrustful, or even opposed, to technological innovations in his sector, the latter being rather perceived as a laggard.

This media coverage, in parallel with significant financial support mechanisms geared towards innovation (research tax credits, FranceAgrimer counters for the renewal of agricultural equipment, SADEA[36] future investment program, French Agri Tech movement, etc.) contributes to the development of a race for technological innovation. **This race for technological innovation generates ever more marked fractures between agricultural situations that no longer understand each other**. This gap, which is not only difficult to bridge for farmers but also for the actors who supervise them, does not facilitate the consolidation, sharing of experience,

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30 Stock, Ryan, and Maaz Gardezi. 2021. "Make Bloom and Let Wither: Biopolitics of Precision Agriculture at the Dawn of Surveillance Capitalism." Geoforum 122: 193–203.

31 Visser, O., Sippel, S. R., & Thiemann, L. (2021). Imprecision farming? Examining the (in) accuracy and risks of digital agriculture. Journal of Rural Studies, 86, 623-632.

32 Pathak, Hari Sharan, Philip Brown, and Talitha Best. 2019. "A Systematic Literature Review of the Factors Affecting the Precision Agriculture Adoption Process." Precision Agriculture 20(6): 1292–1316

33 Higgins, V., van der Velden, D., Bechtet, N., Bryant, M., Battersby, J., Belle, M., & Klerkx, L. (2023). Deliberative assembling: Tinkering and farmer agency in precision agriculture implementation. Journal of Rural Studies, 100, 103023.

34 Duncan, Emily, Alesandros Glaros, Dennis Z. Ross, and Eric Nost. 2021. "New but for Whom? Discourses of Innovation in Precision Agriculture." Agriculture and Human Values (June). https://doi.org/10.1007/s10460-021-10244-8

35 Caquet et al. (2020). Agroécologie - Des recherches pour la transition des filières et des territoires. Chapitre 6 : Contribution des agro-équipements et du numérique à l'agroécologie. Renforcer la prise en considération du vivant. Edition Quae.

36 https://www.economie.gouv.fr/files/files/directions_services/plan-de-relance/CP_20211105_Deux_strategies_acceleration_3e_revolution_agricole_alimentation_sante.pdf

and deployment of existing technologies. This race for innovation also adds an additional risk of generating technological stacking and obsolescence in the sense that the development and renewal of tools are favored (see previous section and upcoming discussions on selected technological innovations). Financial mechanisms, still very much oriented towards technological innovation and too little towards technological transfer in the field (for deployment and concrete handling in agricultural farms) are increasingly accentuating these imbalances.

It is important to keep a step back, assess the issues and make trade-offs, at the risk of finding ourselves in unanticipated problematic situations. What are the risks of deploying or not deploying an agricultural technology? What are the strengths, weaknesses, opportunities and threats of these technological choices? What are the levers to maximize opportunities and limit the associated risks? These are all questions that we invite to be raised systematically and for which we will try to bring elements of discussion.

How to evaluate agricultural technologies ?

1. Methodological proposal for explaining agricultural technologies

The objective of this report is to **provide methodological elements for screening agricultural technologies (Figure 1)**. Our methodological proposal is based on two successive stages, following the panorama of technologies that we have already presented:

- **A high view of the challenges** of agricultural technologies and the levers of action to be activated to ensure that technologies equip and support agroecological trajectories;

- A **more concrete projection of agricultural technologies on farms**, via typical farmer profiles and operational questions, to assess the capacities for technological appropriation in the field.

Overview of agricultural technologies

- **State of the art** of agricultural technologies, in support of decarbonization or adaptation of the sector

Mapping of issues and levers for action

- **Evaluation of technological relationships:** dependencies and synergies between technologies
- **360° challenges of technology deployment:** agronomic, technical, regulatory, financial, etc.
- **Action levers** to exploit strengths and opportunities, and limit weaknesses and threats of deployment

Projection of technologies on farms

- **Adequacy of technology with the agricultural system:** Structure and size of the farm, Location of the farm, Agricultural practices, Regulations and technical supervision
- **Use of typical farmer profiles** to show the diversity of technological trajectories

A. Mapping the challenges of agricultural technologies and the levers for action to support the agricultural transition

For this first step, the description of technological innovations is divided into four parts:

First, we detail the objectives, success indicators and conditions for success of these agricultural technologies. When possible, because the literature exists or because hypotheses have been shared with us, we also make visible a quantitative assessment of the said technology in its capacity to support agriculture in mitigating its GHG emissions and/or in its adaptation to climate change.

Second, we quickly scan the technological dependencies and physical flows (materials, energies, etc.) linked to each agricultural technology. To the extent that The Shift Project takes issue with the double carbon constraint (climate impact and energy dependencies) and the materiality of our uses, we wanted to highlight the components necessary for the proper functioning of the technologies. Mapping dependencies or at least diagnosing them makes it possible to anticipate possible future crises (supply disruptions, etc.) and the risks associated with the use of agricultural technologies in the field.

A third part consists of broadening the spectrum of reflection and setting the framework for the landing of agricultural technologies on the ground.

- A first matrix of issues[37] materializes the first elements of observation (strengths, weaknesses, opportunities, threats). The strengths and weaknesses are to be considered from the point of view of the factors internal to the technology itself. The opportunities and threats relate to their environment in the broad sense. This matrix is held from the perspective of the French system as a whole, and not from the point of view of any specific actor.

- A second matrix of actions shows the strategies to be put in place to activate the transition by using the strengths of these agricultural technologies to exploit the opportunities and limit the threats, and to identify the levers minimizing the weaknesses and potential dangers of the transition. This second matrix makes it possible to operationalize, or at least to initiate avenues of reflection to go beyond the observation.

While the Shift Project's arbitrations are more specifically interested in the energy/emissions/employment triptych, representative of the Shift Project's general approach, these matrices cover a relatively broad spectrum of issues: technical, agronomic, financial, organizational, or even regulatory. These matrices are an opportunity to question with an overall view what would happen to agricultural systems and patterns if the technologies were deployed on a large scale, and if they could impact operating trajectories.

Finally, to the extent that technologies are sometimes part of strong interaction logics, **we seek to map, for each selected technological innovation, the agricultural technologies in the panorama that could be combined with it**. This fourth assessment is slightly different from the second in that it does not seek to describe dependencies (even if two combined technologies can become dependent on each other) but rather to explain the fact that if two technologies combine well, it is conceivable that the development of one of the technologies calls for the development of the second.

B. Projecting agricultural technologies on farms

To give more concreteness to the previous technological descriptions, we propose to question the technological implementation on the ground through typical profiles of farmers. These profiles seek to represent the diversity of French agricultural sectors. The panorama is obviously not exhaustive but seeks to get closer to French agricultural holdings as they exist in 2024, and **not to what French agricultural farms could look like by 2050**.

[37] The SWOT method is a diagnostic tool to characterize the internal context (strengths and weaknesses) and the external environment (opportunities and threats) of a project. This method is applied here to the deployment of agricultural technologies.

We have voluntarily decided not to project ourselves into French transition scenarios (Afterres, TYFA, Sisae, etc.) for at least two reasons. Firstly, because it remains difficult to currently evaluate the share of decarbonization or adaptation enabled by the technologies themselves. Secondly, because the results of prospective studies can be significantly different and do not include the same set of hypotheses, it was not easy to select one over another. We therefore preferred an initial qualitative approach.

To the extent that agriculture is dynamic – farmers develop their agricultural practices according to a whole range of technical, strategic, financial or regulatory criteria – we do not seek to impose a straitjacket on farmers through these typical profiles. **These profiles are porous and trajectories between profiles are obviously possible**. The main objective is to illustrate our point and highlight the main trends. Agriculture is made up of multiple nuances and it is obvious that we could largely color and temper each profile with a multitude of gradients. **This work allows us to discuss the context of use of technologies but also the conditions of relevance of this technology in a logic of transition.**

Within these profiles, technologies are discussed from the angle of four main macro-criteria: the structure and size of the farm, the location of the farm, agricultural practices on the farm, and regulations and technical supervision. These macro-criteria, then detailed in sub-criteria, can be understood as a kind of adoption factors of technologies in the field, it being understood that adoption remains in any case a long process, made of back and forth, and sometimes subjective. Here we seek to question the adequacy between agricultural profiles and technologies.

Following the workshops carried out, we realized that the discussion around a single list of criteria seemed more fluid for certain technologies intended to be used by farmers in the field as new tools in their range (e.g. nitrogen optimization technologies, electric robotics for selective weeding, etc.) than for those that could be quite opaque for the end user (e.g. conventional selection, new genomic technologies, marker-assisted selection, etc.). These considerations may have led us to sometimes change the profiles or discussion criteria a little.

This projection stage allows us to partly move away from a simplistic analysis where technologies are selected and discussed individually, outside their framework of application. For agronomists and zootechnicians who have forged the concepts of cropping system and livestock system for decades, it is the entire socio-technical system that must be considered. It is this whole that reveals the objectives and constraints of piloting the farmer in his particular situation.

2. Step 1 : Evaluation of two technological innovations

For the sake of simplification and because the report has a methodological aim, **we will only detail here two technological innovations for the first stage of the method that we propose**. We refer interested readers to the annexes. The approach can be redeployed for each agricultural technology considered.

A. The example of optimizing nitrogen inputs

- **General description**

Agricultural technologies for optimizing nitrogen inputs are grouped here under a broader scope of technological package since, very often, many technological building blocks must be deployed together to rethink nitrogen fertilization inputs in the field. In the context of large-scale crops, for example, we can find, from the initial recommendation of nitrogen inputs to the application of spreading in the field:

- technologies for initial reasoning of the nitrogen dose (calculation of the total dose or complete management of inputs),
- technologies for adjusting the forecast dose at the end of winter,
- technologies for managing the reserve dose during the season, technologies for helping to adjust spreading equipment,
- decision-making technologies for choosing the best time windows for nitrogen inputs in the plot,
- technologies related to the different forms and formulations of nitrogen to be applied.

These technologies are not necessarily exhaustive and are not suitable for all sectors.

Main objectives: Reduction of N_2O emissions by nitrogen volatilization in the air. Reduction of nitrogen leaching in the soil. Optimization of the efficiency of nitrogen inputs.

Success indicators: Quantity of nitrogen supplied per hectare. Efficiency of nitrogen use by plants. Cost of nitrogen fertilization per hectare (all technologies and associated services included).

Conditions for success: Weather conditions during application. Agricultural equipment and techniques for supplying nitrogen to the field. Rate of mineralization of soil nitrogen.

Potential for mitigating greenhouse gas emissions and/or adapting to climate change: Potential difficulty in quantifying mitigation given the diversity of available tools and their operation.

- **Technological dependencies and associated physical flows**

Measuring raw data generally requires the use of sensors - generally multispectral cameras - embedded in remote sensing vectors (airplane, drone, satellite) or proxy detection (pedestrian sensors, sensors embedded in agricultural machinery). These sensors require electronic chips and other electronic components to operate, and material flows to manufacture them.

Transforming data into biophysical and decision-making information through physical models (inverse radiative transfer models) or simplified models requires computing power (GPU, CPU) and electrical energy to operate the computers.

Locating nitrogen inputs in plots (intra-plot or otherwise) uses geopositioning technologies (GPS or dGPS antenna for classic location to the nearest meter, RTK antenna for fine location to the nearest centimeter, 24 GPS satellites, 26-38 Galileo satellites).

The transfer of information (nitrogen recommendation map or others...) throughout the chain (cloud to machines, machines to cloud, cloud to cloud) can use network infrastructures (cellular networks, starlink, LoRa etc.) which depend on different technologies which then require network infrastructures or satellite communications, themselves consumers of material and energy.

The application of nitrogen input from agricultural equipment to the field can use, depending on the level of technologies envisaged, on-board electronics for modulation at the level of the spreading nozzles (open or closed position, or even intra-nozzle modulation), section cut-off technologies (to close nozzle blocks, for example near the ends of the plot), ISOBUS communication technologies between the tractor and the hitched spreader to finely control the work of the spreader. In addition to the fuel needed to move the agricultural equipment, there are also material flows for the machine parts or the spreading booms used for this agricultural nitrogen fertilization operation.

It should be noted, however, that this technological route could be simplified. Manual modulation of nitrogen inputs, i.e. by limiting the technologies for locating and applying inputs, is possible. However, this requires an understanding of the mechanisms involved by the farmer and more time for the cultivation operation.

- **Mapping of the issues associated with the deployment of technologies for optimizing nitrogen inputs**

A matrix of issues (Strengths, Weaknesses, Opportunities, Threats) of nitrogen input optimization technologies is presented below:

STRENGTHS • Many digital tools for reasoning on nitrogen fertilization already exist • New models for integral nitrogen management are available • The right windows for applying nitrogen are known • Many technical references are available • Nitrogen input optimization technologies are mature in certain agricultural systems	**OPPORTUNITIES** • Investment aid exists for agricultural equipment and digital tools • Certain labels and specifications (e.g. HVE French certification) may require that nitrogen management tools be used • French and European policies are moving towards a significant reduction in the consumption of mineral nitrogen fertilizers. • Field actors are deploying service offers related to the management of nitrogen fertilization. • The increase and volatility of the cost of nitrogen fertilizers may encourage the use of management tools. • N_2O plays a significant role in the agricultural footprint (29% of direct GHG emissions in 2022[38] in France)
WEAKNESSES • The complete technological system is expensive • Nitrogen models are adapted to certain crops in particular and to single-species populations • The technological system requires strong	**THREATS** • Nitrogen management technologies are developed and supported only in certain agricultural sectors. • The complete technological system of nitrogen management can contribute to additional indebtedness of farmers

[38] Citepa, 2024. Rapport Secten – Emissions de gaz à effet de serre et de polluants atmosphériques 1990-2023.

interoperability (for recommendation maps, between tractors and spray booms, etc.) • Nitrogen management tools are still little adopted in the field (depends on sectors and crops) • There is a sometimes significant time latency between the request and receipt of nitrogen recommendation maps • Of all the nitrogen fertilization management tools, many tools do not actually do the same thing • Nitrogen management tools are sometimes misused to remove the cap on regulatory doses of nitrogen input	• Nitrogen management technologies, if they are only available in certain sectors and crops, can contribute to strengthening the dominant agricultural model • The use of nitrogen management technologies can slow down the development of alternative practices that would require less nitrogen inputs (direct seeding under permanent cover, legumes and other companion plants, etc.)

A matrix of action levers to exploit the strengths and opportunities of agricultural technologies for optimizing nitrogen inputs while limiting weaknesses and threats is presented below:

STRATEGIES FOR EXPLOITING OPPORTUNITIES THROUGH STRENGTHS • Have different levels of labeling for nitrogen management tools (COMIFER[39] in France) • Expand experiments with nitrogen management tools in farmers' operational conditions	**THREAT PREVENTION STRATEGIES USING OUR STRENGTHS** • Develop nitrogen recommendation models for more diversified crops • Offer less technological nitrogen management services (by ensuring a good climatic window for nitrogen application, by modulating inputs with lighter geo-positioning technologies, etc.) • Provide financial support to farmers on nitrogen management tools subject to obligation of results
STRATEGIES FOR EXPLOITING OPPORTUNITIES TO MINIMIZE WEAKNESSES • Force interoperability by using standard formats for exchanging recommendation cards • Improve logistics and after-sales service for suppliers of nitrogen recommendation cards • Grant bonuses to farmers who split nitrogen inputs even more than what is recommended by the models	**STRATEGIES TO MINIMIZE POTENTIAL DANGERS AT THE INTERSECTION BETWEEN WEAKNESSES AND THREATS** • Train agricultural stakeholders in the links between nitrogen and agronomy • Encourage farmers to monitor changes in nitrogen inputs over time on farms • Separate the sale and advice on nitrogen products or make the sale conditional on certified advice • Train agricultural stakeholders in the most efficient nitrogen input techniques

- **Combination of technological levers**

Nitrogen supply technologies can be combined with:

- crop rotation or crop modeling technologies to direct nitrogen inputs towards future crops
- optimized conventional and/or NGT selection technologies to direct inputs towards the nitrogen needs of these varieties
- precision irrigation technologies in view of the intimate relationships between the nitrogen and water cycles

[39] https://comifer.asso.fr/

B. The example of new genomic technologies

- **General description**

New Genomic Technologies (NGT or NBT – New Breeding Techniques) are part of a set of tools for selectively editing a genome. These technologies make it possible to induce targeted modifications to the genome (by adding, modifying, deleting genes) in order to search for specific traits. This precision needle requires very detailed knowledge of the genes and alleles of the plants studied, and an ability to make the link between favorable alleles and favorable traits on the plant in fine. This approach can greatly benefit from inter-species knowledge and research work carried out upstream on model plants. These new genomic technologies stand out from, while complementing, other agricultural technologies such as conventional breeding (see other technological case study studied), marker-assisted selection (MAS), mutagenesis, or transgenesis.

Main objectives: Adaptation of plants to climate change. Better efficiency of water or nitrogen use of plants. Minimization of soil work (fuel saving). Reduction of the use of phytosanitary products (selection of resistance to certain pests/diseases). Better adaptation of plants to association contexts (legumes or other species inserted in companion plants).

Success indicators: Improved resilience to stresses due to climate change. Profile of the varieties developed (traits, species concerned). Maintaining a wide diversity of breeders and increasing the number of species cultivated. Maintaining a diversity of food sectors (conventional, organic, GMO-free, etc.). Improved plant production (better digestibility, fewer post-harvest chemical treatments, etc.).

Conditions for success: In-depth knowledge of the plant genome. Mono- or oligogenic traits (in the sense that the traits or characters must be influenced by one or more genes) to be able to edit the genome. Upstream investment to develop breeding programs. Available methods for cell regeneration from in vitro cultured tissues. Strong interactions between academic and applied research.

Potential for mitigation of greenhouse gas emissions and/or adaptation to climate change: very difficult to quantify. Will depend on the direction of selection and the level of realization of promises.

- **Technological dependencies and associated physical flows**

In addition to the development of research laboratories and the need for expertise and genomic modification tools, new genomic technologies do not seem to be as sensitive as other technological innovations to physical flows.

The use of new genomic technologies could, however, call for exacerbating the traceability of production across the entire food system, thus requiring the deployment of extensive digital infrastructures (fine identification of batches, database, etc.) from breeder to consumer.

- **Mapping of the issues associated with the deployment of technologies for new breeding techniques**

A matrix of issues (Strengths, Weaknesses, Opportunities, Threats) of new genomic technologies is presented below:

STRENGTHS	OPPORTUNITIES
• NGTs are routinely used in fundamental research • NGTs provide the ability to link favorable alleles with favorable traits (precision needle) • NGTs offer the potential to develop varieties adapted to climate change and induced abiotic stresses • NGTs allow the acquisition of transversal knowledge between species • It is theoretically possible to reproduce the same modifications with NGTs as with classical selection • NGTs are potentially faster than selection at the level of one or several traits simultaneously but not necessarily at the more global scale of selection or for isolated mutations • NGTs offer the ability to produce entirely new traits (or new in the variety)	• A global dynamic is underway on NGT (but heterogeneous between countries) • Feedback is available on GMOs, so as not to reproduce the same deleterious effects • Climate change (and its speed) increases the expectations of NGT technologies: crystallization at the selection level • NGTs make it possible to obtain detailed knowledge of the genome of certain plants, which is constantly increasing. • NGTs offer the possibility of accumulating a lot of phenotyping and envirotyping data in the face of increasingly fine genetic and genotypic data. • Artificial intelligence and protein structure modeling technologies can support the development of NGTs
WEAKNESSES	**THREATS**
• NGT technologies are not at the peak of their technological maturity • It remains difficult to organize the traceability of NGT plants across the entire agri-agro chain (unless mandatory declaration) • It remains difficult to know the optimum potential of a plant in the future • Knowledge of the plant genome is heterogeneous • It is more difficult to target criteria related to climate change because a large number of genes are involved • The development of NGT plants is not feasible on the farm and requires developed R&D tools (lab and others) • NGTs run the risk of maladaptation of the plant depending on the traits developed • NGTs require significant R&D work and financial investments. • NGTs can lead to potential health risks related to the use of genome modification tools (off-target and on-target effects, allergenicity, toxicity, etc.). The edited genome and any unwanted or desired mutation should nevertheless be eliminated by backcrossing. NGTs can lead to potential environmental risks (invasive effects, gene flow, destabilization of ecosystems, etc.)	• NGTs carry the risk of increased patentability and lack of widespread access to solutions (potential conflicts in terms of transparency and intellectual property) • The seed sector risks becoming even more concentrated and reducing the number of players involved • NGTs are currently dependent on technologies developed abroad • There may be a risk of a shortage of genetic modification tools for R&D and the use of NGTs • The shortcomings of GMO production and associated sales systems could also be found with the use of NGTs • R&D around NGTs could be oriented towards specific unsustainable practices/species (financial or other opportunities) • The social acceptability of NGTs is not guaranteed

A matrix of action levers to exploit the strengths and opportunities of new genomic technologies while limiting weaknesses and threats is presented below:

STRATEGIES FOR EXPLOITING OPPORTUNITIES THROUGH STRENGTHS	THREAT PREVENTION STRATEGIES USING OUR STRENGTHS

• Work on the issue of non-patentability, in connection with the experience of GMOs (significant market concentration in the USA) to guarantee access to NGT traits for all breeders. • Orient the development of NGTs towards decarbonization needs • Block the development of NGTs towards varieties tolerant to herbicides (and other categories of phytosanitary products)	• Definition of a regulatory framework preventing the combined sale of NGT and pesticides, and limiting the development of herbicide-tolerant varieties • Promote the development of non-patented technological tools and varieties supported by public authorities • Orient private and public research towards orphan varieties and sustainable traits • Establish decentralized decision-making centers with shared multi-stakeholder governance
STRATÉGIES POUR EXPLOITER LES OPPORTUNITÉS POUR MINIMISER LES FAIBLESSES • Develop basic research, public-private partnership to better understand genomes • Develop a regulatory framework that guarantees the best development of the opportunities offered by NGTs and maintains a high level of health and environmental safety	**STRATÉGIES VISANT À MINIMISER LES DANGERS POTENTIELS AU CROISEMENT ENTRE FAIBLESSE ET MENACES** • Provide monitoring of the health, environmental and socio-economic effects of NGT • Organize a broad debate with the whole of society on the advisability of using NGT or not by popularizing the complementary varietal creation character of selection and domestication. • Define a regulatory framework that allows consumer information • Support peasant seeds

- **Combination of technological levers**

To the extent that new genomic technologies require detailed knowledge of the genome, these tools seem consistent with bioinformatics and high-throughput genotyping technologies. The relationships between the genotype and plant characteristics and traits also call for the use of high-throughput phenotyping tools (in laboratories, experimental farms, and more broadly with large experimental networks capable of integrating the relationships between the genotype and the environment). The ability of plants edited by NGTs to use nitrogen or water resources more efficiently could be measured with the range of technological tools presented in the overview in the first section of the report (precision irrigation technologies, nitrogen input optimization technologies, etc.).

The ability of new genomic technologies to combine with tools that may seem less sophisticated in conventional breeding (see other technological case studies) will depend on the directions given to NGTs. This coupling could be encouraged and prioritized in order to accelerate the obtaining of results for farmers. In this specific case, it must be considered that it is indeed measured and quantified genetic progress that has also made it possible to develop and improve conventional selection (via catalogue) which today uses modern techniques with molecular marking and genomic selection.

Feedback on the first stage of the method: A step back on agricultural technologies

This first stage of our methodology has made it possible to initiate the debate on issues that go beyond purely technological considerations. Through two technological examples (here the optimization of nitrogen inputs and new genomic technologies), **the matrices of issues and actions demonstrate the fact that agricultural technological proposals cannot simply be reasoned all things being equal**. It is therefore necessary to discuss regulatory, socio-technical, financial, organizational, or even human issues. The issues of technological dependence and combinations of technological levers (also highlighted in this first stage) have made it possible to better map the technological relationships involved.

The elements discussed in this first stage nevertheless sometimes remain a little too general - in the form of observations - and do not allow us to sufficiently appreciate the landing of technologies on the ground, in conditions that approach those experienced by farmers. The second stage of our method seeks to answer this in part.

3. Step 2 : Projection of two technological innovations in agricultural farms

For the sake of simplification and because the report has a methodological aim, **we will only detail two technological innovations again in the second stage of the method that we propose.** The approach can be redeployed for each agricultural technology considered.

Because the report seeks to demonstrate the applicability of the method in various case studies, the projection is not carried out on the same technological case studies as previously. **If the previous section focused on nitrogen input optimization technologies and new genomic technologies, this section focuses on electric robotics for selective weeding and conventional selection.**

The stakes and findings matrices of these two new examples are provided in the appendices for interested readers.

A. The example of electric robotics for selective weeding

This technological innovation was not described in the previous section in order to diversify the case studies discussed in the report. We refer the reader to the appendices where the matrices related to robotics are presented.

Although the definition of robotic systems is still debated for reasons of mobility, degree of autonomy, learning capacity, extent of decision-making or the ability to pre-program the robot, we have considered robots here in a fairly broad sense. In this case study, robots are mechatronic systems capable of performing a weeding action fairly autonomously under human supervision (in collaboration or not) for applications in plant and animal contexts. In this case study, the robots are powered by electrical energy.

1. Detailed analysis of the robotics case study

The following table presents reading elements with regard to the main macro-criteria and sub-criteria linked to the use of electric robotic tools for selective weeding:

Macro-criteria	Sub-criteria	Details
Structure and size of the farm	Splitting and moving away from the plot	Moving robots between plots (by tractor or trailer) can be difficult, especially if the plot fragmentation is significant. Environmental impact of moving robots by towing between plots.
	Farm size	Potentially interesting for farms with a large surface area to install electric charging stations for robots. The working width and work rate parameters of the robotic tool can allow working in more or less large plots.
	Amortization of technologies	Robotic tools are more difficult to amortize on small surfaces and very diversified small farms. Robots are difficult to amortize if there is no economy of scale for manufacturers (need for many robots sold and covered areas).
	Heterogeneity of soil and climate conditions on the farm	Not really applicable here.
	Condition of the equipment already existing on the farm	The robot can be added to the existing agricultural equipment (with the tractor, especially for large crops). Modular or open-source bricks can limit the phenomenon.
	Relations with labor and skills	Specific skills for mastering the robot, Need for training and skills for a farm that is not mechanized at the start (potentially stronger impact on market gardening). Potential attractiveness of robotic tools for older farmers if there are no successors or for young people looking to set up.
Location of the farm	Local soil and climate conditions	Need for clean and not too uneven terrain. Difficulty operating the robot if conditions are difficult (rain, slope, heat waves, etc.).
	Proximity to energy networks	Need for one or more high-power electrical sources for rapid recharging (shed, agricultural building, etc.). Possibility of having a solar panel on board the robot to gain a little autonomy (problem of panels that cannot recharge the robot at night). Obligation to go and recharge (potential need for rapid charging). Easier to install robots if networks are already accessible nearby.
	Local financial aid	Support from local authorities, aid to regions to facilitate the installation of robots.
	Isolation of the farm	No after-sales service or robot repair service if isolated territory, Need for a well-connected dealer network.
	Relations with local sectors and outlets	Need for homogeneity of local sectors to facilitate the work of dealers.
	Local white zones	RTK navigation problem if white zone (but few white zones that do not have access to it). Good connection required for video monitoring of the robot's work (if no supervision in the long term). Either 5G antenna or on-

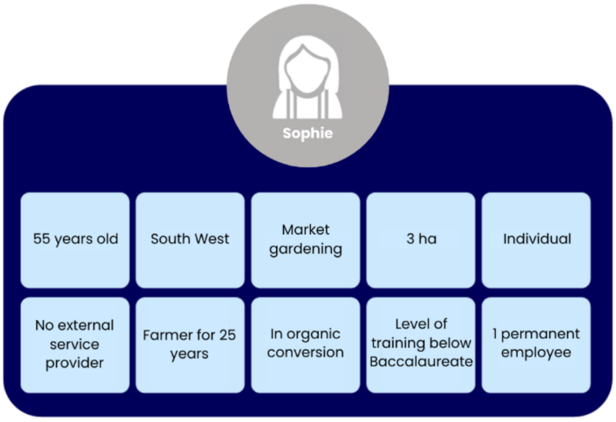
		board calculation. White zones require on-board processing of information if there are no very high-speed connections (it is nevertheless complicated to completely deport the calculations).
	Relations with neighboring farms	Service companies that can appropriate the robots (more for large vegetable crops), Possibility of developing robot sharing models or functional economy.
Agricultural practices	Compatibility with organic, Soil Conservation Agriculture, agr-ecological systems, etc.	Possibility of catching up on mechanical weeding that would have been missed. Diversity of forms of selective weeding. Potentially multi-purpose robots for operations other than weeding. Would allow the redeployment of routes that would require a lot of manual weeding.
	Organization of work on the farm	Robot supervisor who can diversify his tasks in the field. Potentially in the long term a robot that works 24/7. Reorganization of working hours and delegation of tasks on the farm.
	Working time	Slow work rates that are unacceptable for humans (especially when mechanized). Too small a working width and too low a work rate would especially impact large areas, especially if the working time windows are short.
	Adaptation to existing routes	Depends on the system you start with: perhaps simpler on large vegetable crops because the system is already mechanized. Difficulty to intensify as much as with manual labor. Potential need to adapt the cultivation systems on site to the operation of the robot. Not very suitable for market gardening, living soil with thick mulch or other
Regulations and technical supervision	Justification of cultivation practices	Operator required to monitor robots (but this could change)
	Specification constraints	May encourage the abandonment of certain phytosanitary products and encourage conversion to organic farming.

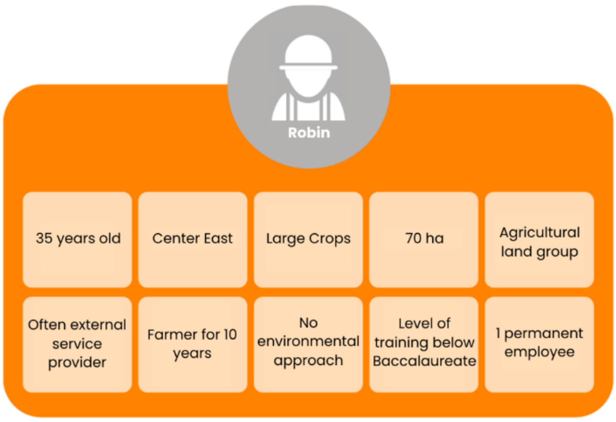
Table 4 : Detailed analysis of the implementation of robotic tools for selective weeding on farms

2. Short scenario of two agricultural profiles around robotic tools for selective weeding

Two profiles are imagined here:

- Small-scale market gardening
- Open-field vegetable production





The spatial organization and larger size of Robin's farm impacts the logistics of the work of his robotic tool. The fragmentation of his plots calls for using a trailer to move his robot between plots (as long as regulatory constraints are not lifted on the autonomous movements of robots). The size of his farm facilitates the amortization of a robot in the long term but also requires the robotic technology to work at a sufficiently high rate to carry out weeding operations within the imposed time windows. The still single-task robotic tool is added to the agricultural equipment present on the farm, but Robin's already mechanized cultivation itinerary facilitates the integration of the robot into the work on the farm. Robin's plots are located less than 2 km from an electrical network, which facilitates a potential connection directly to the plot and an electric recharge of the robot in the field. Robin's farm is a few kilometers from a large country town. A robotic agricultural equipment dealer works in the region and works on several farms in the area.

Sophie benefited from a local support window for the purchase of agricultural equipment to be able to invest in this robotic tool. The 3 hectares of Sophie's farm are in one piece. The permanent employee on Sophie's farm gains in working comfort. The robot's work rate is quite low but the employee spends more time observing the proper establishment of crops and the departure of disease or pest outbreaks. This employee has undergone several training sessions to be able to support the robot in its work. Sophie decided to replant certain crops for which prior manual weeding was arduous and time-consuming. Unable to connect her farm to an electrical network, Sophie had to equip herself with two sets of batteries recharged and used alternately. Sophie's farm, more isolated, is less well served by maintenance teams for these robotic tools. Several hours are needed to have an operator capable of working on your plots.

B. The example of conventional selection

This technological innovation was not described in the previous section in order to diversify the case studies discussed in the report. We refer the reader to the appendices where the matrices related to robotics are presented.

In a few words, in this case study, conventional selection is considered as the set of techniques for crossing or natural hybridization of the genetic material of a plant or animal, supplemented by molecular marking and genomic selection that ensure better consideration of the relationships between the genotype and the environment. These approaches are distinguished from other selection innovations such as genome editing (such as the new genomic technologies that are discussed in a case study of the report) even if they may share the same objectives.

1. Detailed analysis of the conventional selection case study

The following table presents reading elements with regard to the main macro-criteria and sub-criteria linked to the use of conventional selection technology.

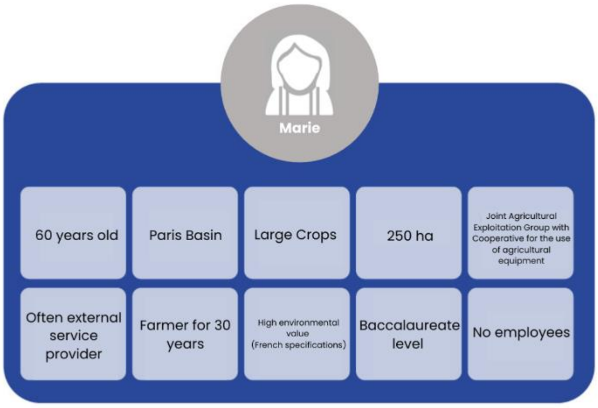
Macro-criteria	Sub-criteria	Details
Structure and size of the farm	Splitting and moving away from the plot	Not really applicable here.
	Farm size	Optimized treatment period increasingly short and random, therefore more complicated for large farms. The agricultural itinerary will be all the more simplified if there is a dependence on sorting organizations. The establishment of farm seeds can be easier on small farms unless the farm uses a service provider or adheres to a Agricultural Equipment Use Cooperative for this action.
	Amortization of technologies	Large farms could better optimize the integration of seeds (farm seeds). The choice between farm seeds and certified seeds is multifactorial. The ideal would tend towards the combined use of farm seeds and certified seeds to cross economic advantages, varietal renewal, simplicity and autonomy.
	Heterogeneity of soil and climate conditions on the farm	Not really applicable here.
	Condition of the equipment already existing on the farm	Farms that have storage capacity have greater room for maneuver and weight in their decisions.
	Relations with labor and skills	Not really applicable here.
Location of the farm	Local soil and climate conditions	Capacity of conventional selection to develop varieties adapted to certain climates (on issues of precocity for example).
	Proximity to energy networks	Carbon storage is increased if there are no more constraints on water availability.
	Local financial aid	Potential integration into local food plans and climate plans. National aid: the protein plan helps with the selection of legumes.
	Isolation of the farm	Not really applicable here.
	Relations with local sectors and outlets	Impact of the choices of a local cooperative on seed multiplication or other. Dependence on local storage organizations (and question of bonuses associated with routes if the farm chooses this or that variety).

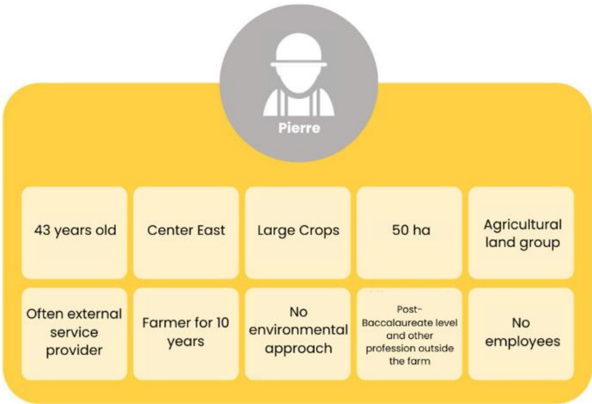
	Relations with neighboring farms	The question of pooling knowledge on varieties is important (particularly in alternative networks). Sharing knowledge and formalizing local knowledge (fear of recovery/monopolization of equipment and knowledge by external companies, risk of uberization of work by taking advantage of the actions of networks of small breeders). Possibility of management by forms of collective agricultural organization (e.g.: Potatoes Netherlands).
Agricultural practices	Compatibility with organic, Soil Conservation Agriculture, agr-ecological systems, etc.	Current production methods are not the most economical in inputs. Reflections on the farm on the mixtures most suited to local pedoclimatic specificities. Elements of sustainable agriculture added to the criteria for registration in the catalog. Need for specific varieties for direct seeding. The farmer is in control of his choice (within a certain framework with regard to the existing catalogue) but has only marginal control over the evolution of selection activities if they are not carried out locally.
	Organization of work on the farm	Not really applicable here.
	Working time	Multiplication work can represent an increase in labor (for example: castration of corn).
	Adaptation to existing routes	Varieties can modify or impact the structure of plants and therefore change the technical structures on the route.
Regulations and technical supervision	Justification of cultivation practices	Not really applicable here.
	Specification constraints	The French red label is considering removing wheat shorteners from the specifications. Millers and brewers often impose lists of varieties. Constraints are possible if the appropriate genetics are available. New varieties can also require defining new routes and be the source of new points of vigilance.

Table 5 : Detailed analysis of the implementation of conventional selection on farms

2. Short scenario of two agricultural profiles around conventional selection

Two profiles are imagined here:





Marie obtains her supplies from her cooperative, which interacts with a large seed company. Marie believes that her plant material does not need to have been produced in the region to be suitable for her farm. She follows the advice given by her technical institutes for choosing varieties suited to her soil and climate conditions. These seeds nevertheless allow Marie to be more efficient throughout her cropping process because her time windows are increasingly shorter and more random. The seeds are relatively inexpensive because the breeding company has recouped its initial investments. Despite this, these breeding efforts must continue over time to maximize the adaptation of future varieties. Marie receives sector premiums from her cooperative (to which she supplies her crops) for the varieties she uses - varieties promoted by her cooperative to several neighboring farmers. The conventional breeding practices ultimately used by Marie influence her farming trajectories, in particular because her production methods are not the most economical in terms of inputs, even though she has adopted an HVE certification approach (French certification). With the size of her farm and her potential storage capacities, Marie is thinking about integrating part of the seed production activity on her farm in the long term.

Pierre maintains a fairly close relationship with the breeding organization that he favors. The breeding company works on varieties that are adapted to the territory where the farm is located. Pierre has spent time thinking about the most locally adapted mixtures. Without directly doing varietal selection in the strict sense of the term (which is carried out by the breeding organization with whom he works), Pierre mixes varieties and carries out a kind of mixture selection in this sense. These more specific varieties require Pierre to rework part of his itineraries and technical structures. Pierre is satisfied with the direction given to his farming trajectory even if the concrete assessments of the economic and environmental validity of the varietal choices have not been finalized. Pierre is part of a network of farmers within which he shares the knowledge developed around his varieties. He also discusses with his cooperative to simplify the specifications in place in order to facilitate his practice developments.

Feedback on the second stage of the method: A dive into farms

This second stage of our methodology made it possible to question in more depth the capacity of technologies (here conventional selection and electric robotics for selective weeding) to fit into the landscape of farms. Questioning the interaction of technologies with field factors (the size and structure of the farm, the location of the farm, the agricultural practices used, the notions of regulation and technical supervision involved) promotes a concrete and down-to-earth exchange with field stakeholders.

The agricultural profiles that we have invoked show different trajectories of technological integration and thus demonstrate the diversity that technological systems can take on the ground. Without judging here the relevance or not of these technologies to support the agricultural transition, we show that there are perhaps as many forms of technological appropriation as there are agricultural systems.

Considering the conditions for implementing agricultural technologies

1. A need for a method to analyze agricultural technologies

In this note, we advocate that stakeholders involved in the development of technological innovation systematically assess the impact of different technological options. We have proposed a methodology to assess the landing of technologies on the ground. **This method is all the more important since it does not seem that the main stakeholders supporting the deployment of agricultural technologies** (financing stakeholders, business chairs, agritech or biotech groups and collectives, etc.) **have a reading grid to assess the relevance of a technology to support the transition of the sector, or even to simply identify its negative externalities or rebound effects.** It is therefore to be feared that decisions to support certain innovations (via hubs, incubators, banks, etc.) are motivated more by opportunism or by media hype than by the actual contribution expected to the transition trajectories. To the extent that these actors participate in changing or reconfiguring agricultural trajectories, it seems important to take a closer look at the quality of the arguments that govern these decisions[40].

As a reminder, the methodological approach discussed in this report distinguishes two main stages aimed at scrutinizing an agricultural technology.

The first stage consists of four sub-parts:

- providing a general description of the technology to ensure its understanding,
- specifying the technological dependencies and associated physical flows to assess the risks of introducing the technology into an energy-climate transition in agriculture,
- mapping the issues associated with deploying this technology, and
- evaluating the potential synergies with other technological levers to the extent that the technological combination may also prove relevant (we will discuss this later).

Mapping the issues and levers for action is certainly the most delicate and important section. It requires not stopping at a simple technological reading of the situation, but rather opening up the field of possibilities and taking an interest in the regulatory, socio-technical, financial, organizational, or even human issues with which agricultural technologies can interact. It is therefore an opportunity to also gather *ex-ante* knowledge on the positive and negative effects of agricultural technologies. This first step is not only an observation – in the form of a mapping of issues – but also an implementation, in the sense that it must be possible to respond to all the issues with clear and acceptable proposals, otherwise the technological deployment could be called into question.

[40] Klerkx, L., & Villalobos, P. (2024). Are AgriFoodTech start-ups the new drivers of food systems transformation? An overview of the state of the art and a research agenda. Global Food Security, 40.

The second step proposes to go a step further in order to test the capacity of agricultural technologies to adapt to the existing terrain, in all its diversity. Using four macro-criteria (structure and size of the farm, location of the farm, agricultural practices, regulations and technical supervision) and associated sub-criteria, we call for concrete questions on how farm trajectories will or will not mix with technological trajectories. To give even more life to this method, we propose to add profiles – supposed to represent an agricultural reality (more or less local) to be able to project technologies into daily agricultural use and discuss it.

The proposed method is of course open to criticism because agricultural transformation is mainly discussed from the perspective of technological innovations, and technologies have relatively little meaning when they are removed from their conditions of existence on the farm. **The second stage of our method nevertheless allows for a broader discussion within the framework of the farm's agricultural system since much more explicit field criteria are addressed.**

To the extent that the deployment of agricultural technologies necessarily depends on the context in which they are inserted, **we will not be able to depart from a case-by-case approach to judge the interest of a particular technology**. We need an assessment of the energy-climate relevance (here because we are dealing with the subject as part of the work of the Shift Project) of the technologies that is systematic (for each technology, each particular case, each given application, etc.) and exhaustive (taking into account direct impacts and indirect and systemic impacts).

In general, **this method must be part of a responsible research and innovation**[41] (RRI) approach. The four pillars of a responsible research and innovation approach: [1] anticipation (of risks), [2] inclusion (many actors around the table), [3] reflexivity (to assess whether mutually beneficial trajectories are followed) and [4] responsiveness (ability to respond quickly to the problems caused) must be regularly questioned[42]. **This approach and the results that emerge from it must be made transparent and must seek to mobilize as much as possible diverse colleges of actors** (in terms of skills and work discipline). There is currently no obligation (and even very little incentive) for these questions to be raised by the actors of the technological ecosystem.

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41 Bellon-Maurel et al. (2022). Digital revolution for the agroecological transition of food systems: A responsible research and innovation perspective. Agricultural Systems, 203, 103524.

42 Klerkx, L., and Rose, D. (2020). Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways? Global Food Security, 24.

2. Reflecting on the technological orientations of agricultural systems

A. Technologies to consider in the service of border transition scenarios : the example of the work of the Shift Project

The initial plan for this note was to assess how the four scenarios discussed in the Shift report "For a low-carbon, resilient and prosperous agriculture" (food sovereignty, energy sovereignty, food security, conciliation scenario) could or could not guide certain technological developments. It was also an opportunity to ask whether technological trajectories could themselves influence scenario choices in the sense that it is never really clear whether technologies "enable" or "are enabled by".

While we have noted that the proposed scenarios were not sufficiently contrasted from a technological point of view in the sense that they do not impose a technological shutdown or deployment, we can nevertheless provide some examples and discussion points.

The Shift Project envisages significant reductions in the use of mineral nitrogen fertilizers. While part of this decrease is to be found in the massive planting of legumes and associated crops that The Shift Project recommends, it remains the case that optimizations of nitrogen inputs are expected. Nitrogen fertilization management technologies and fertilization input technologies by agro-equipment should therefore be considered in a logic of reducing dependence on mineral nitrogen. Full nitrogen management (via dynamic models), intra-plot modulation of nitrogen inputs or even the burial of nitrogen are all approaches likely to support the sector in its transition. It should be remembered that strong assumptions of an increase in biomass are made in the scenarios. Under the constraint of mineral nitrogen fertilizer, the precision of inputs and the efficiency of nitrogen use by plants will be all the more important.

Organic farming plays a significant but not predominant role in the biases of the agricultural practices envisaged (around 25%). From a technological point of view, two trends can thus be considered. On the one hand, the need to continue to mobilize existing technologies on other production systems since they will always continue to exist. On the other hand, the need to deploy technological tools to support the organic sector, such as low-input systems, which currently require additional administrative tasks and traceability requirements (controllers, certification bodies, cooperatives, etc.), and to raise awareness among technology designers of the specificities of organic farming[43].

The strong development of legumes and crop associations (wheat/peas, wheat/lentils, etc.) **may require technological efforts upstream from the agri-food industries to ensure both that varieties adapted to interspecific mixtures are available and that no legume residues are found in cereal stocks sent to processors after sorting**. Developments in optical sorters can thus be expected to make it possible to practice associations of species and varieties adapted

[43] Schnebelin, Éléonore, et al.. 2021. "How Digitalisation Interacts with Ecologisation? Perspectives from Actors of the French Agricultural Innovation System." Journal of Rural Studies.

to local conditions in a majority of plots[44]. This development of legumes will have to be accompanied by significant efforts in varietal selection and genetic improvement of legumes, which are still too little present at present. This is materialized in particular by material deficiencies for geneticists and breeders working on legumes (capacity to have molecular markers and other technologies for identifying alleles of agronomic interest).

Let us nevertheless add here the need for all links in the agricultural chain to play their role. To what extent should the transition issue be focused on technological issues and not on challenging the demands of downstream stakeholders, consumer demands or nutritional issues?

For example, we could question the legitimacy of the development of densimetric and optical sorters mentioned above to avoid legume residues in crop associations at the exit of the plot. It is indeed conceivable that the agri-food industries will question the norms and standards of products at the input of their chain or develop their product ranges. Citizens can also be expected to change their consumption expectations to facilitate and support the landing of these associated crops; without necessarily needing to develop massive sorting infrastructures. The time windows of agricultural routes are getting shorter and yet, downstream players are increasingly demanding on the quality of harvests (for example, in the past, we were allowed to harvest more humid products). Storage organizations close earlier at night, which leads to increasing the size of the machines to compensate for the human resource limitations of these cooperatives.

In the context of animal production, it is clear that technological deployment is simpler when the animals are in buildings, simply because the technical constraints are fewer and because the system as a whole is better controlled. A scenario of strong food production intended for export will certainly require a work organization linked to massively deployed capital-intensive technologies (robots, modulation of animal feed, covering of effluent storage pits) to both produce and limit greenhouse gas emissions. Technology helps here to satisfy the breeder's demand for monitoring and occupation, especially in the case of large herds (and this on several sites for example). In the same way, the valorization of co-products, in particular oilcakes, for animal feed, can also call for an increase in the number of animals in buildings. With this in mind, it is mainly digital technologies for optimizing logistics and managing flows that will certainly be developed.

The Shift Project calls for an upward review of mixed crop and livestock farming and thus bets on a redistribution of livestock across French territories. We can therefore assume that the expected production units and associated technologies will be smaller and mobile[45]. Examples of mobile milking robots in the territories are certainly interesting to explore. Agricultural works companies will certainly be much more in demand in this context because mixed crop and livestock farmers will prefer to prioritize their investments, for example by favoring an agricultural building for livestock farming over an agricultural machine for plant production. The technological deployment in Agricultural works companies (on-board sensors on machines, high-performance agricultural equipment, etc.) could also contribute to reducing the impacts of cultivation practices.

The last example is carbon storage in agricultural wells, which is of particular importance in the Shift Project scenarios. If it is once again accepted that it is agricultural practices and not technologies that are storage, the technologies that will accompany carbon storage practices in the soil will be favored. In addition to digital tools for monitoring the implementation of these

[44] Caquet et al. (2020). Agroécologie – Des recherches pour la transition des filières et des territoires. Chapitre 6 : Contribution des agro-équipements et du numérique à l'agroécologie. Renforcer la prise en considération du vivant. Edition Quae.
[45] La France Agricole (2024). Numéro 4077 - Dossier « Valoriser l'herbe en traite robotisée »

agricultural practices (via Sentinel-2 constellations for example), digital tools to support the collection of agronomic data to feed into models for calculating stored carbon and/or avoided emissions, and for connecting agricultural stakeholders for carbon payment could make sense[46].

B. Combining agricultural technologies and coupling forms of innovations

In this note, the majority of technologies are studied in silos (each one being analyzed alone). However, we repeatedly mention the fact that agricultural technologies are intertwined because they depend on other technical architectures or specific technologies and can feed off them to a greater or lesser extent.

The combination of agricultural technologies is thus a case to be studied as soon as an alliance is deemed relevant, and can broaden the spectrum of data collected, modeled information, or field actions. This is also why the technology analysis methodology that we propose mentions, in the second step, the search for potential synergies between agricultural technologies. As examples of combinations:

- The localized supply of mineral nitrogen fertilizers in large-scale crops can be obtained by using a combination of satellite technologies to capture biomass levels, inverse radiative transfer models to generate a nitrogen recommendation, and agricultural fertilization equipment to modulate inputs in the field. This cross-referencing makes it possible to spatialize nitrogen inputs on plots according to local nitrogen needs.

- GPS tracking technologies can be used in conjunction with remote sensing technologies (satellite, aircraft, drone) to cross-reference the passage of animals in agro-pastoral systems with geomatic indicators of the grazed resource. This cross-referencing would, for example, make it possible to discriminate between certain plant patches to be protected and others where grazing pressure can be increased.

Our approach focused on one form of innovation among others: technological innovations. Other approaches to agronomic innovation (relay-cropping, direct seeding under cover, associated crops and service plants, etc.), or even organizational ones (supply circuits, pooling of tools via collective organizations, etc.) are quite capable of facilitating agroecological trajectories.

It should be kept in mind that these innovations are entirely compatible with each other, and that it is above all innovation systems, combining different techniques and organizational methods, that will be able to respond to both the different challenges and the diversity of specific local situations. Technologies, through their very varied compositions, can help support these other forms of non-technological innovation. These coupled innovations (couplings between different forms of innovations and couplings at several levels of food systems)

[46] Aspexit (2021). La course au carbone en Agriculture. Accessible en ligne : https://www.aspexit.com/blog-agriculture-et-numerique/

can help to remove constraints from the current system or to generate new opportunities for innovation[47]. For example:

- Digital technologies can support the deployment of short-circuit or network organization modes and facilitate the exchange and sharing of information between peers.
- A peasant agro-equipment can be developed specifically to support a direct seeding practice, while being sufficiently ergonomic to limit the difficulty of field work.

C. Adopting a principle of sobriety for agricultural technologies

The case studies presented in the report demonstrate the great difficulty in obtaining consolidated figures on the mitigation and adaptation capacities of agricultural technologies. These assessments are all the more complicated given that the Agritech and Biotech ecosystem is evolving very quickly, that technological tools can serve several functions at the same time (saving time, reducing drudgery, saving on inputs, etc.) and that rebound effects are never far away[48,49]. **Although it is relevant to focus on systems, their interactions and their general evolution rather than on technologies taken in isolation, it will certainly be necessary to go through a phase of precise quantification of technological effects, all other things being equal, to assess the place of these technologies in the sector's transition.**

It would be utopian to base all agricultural decarbonization efforts on agricultural model transformations without any space for agricultural technologies, and certainly dystopian to imagine a decarbonization only enabled by agricultural technologies. **The reflection on the future of agricultural technologies will necessarily have to invest in the field of sobriety.**

These sobriety efforts must be thought of on several scales: individual sobriety, collective sobriety, and structural sobriety. For example, it is clear that French agriculture is over-mechanized in terms of agricultural equipment[50]. Tractors are often overvalued compared to the tools they are supposed to attach. Part of the fleet is largely underused.

- For example, **individual sobriety** will involve, for a farmer, reasoning about the act of purchasing his or her agricultural equipment, more detailed diagnostics of the suitability of tractors and tools according to the agricultural practices to be carried out and better use of his or her fleet (checking tire inflation, using the tractor in the right ranges, etc.).
- **Collective sobriety** will be demonstrated by a reorientation of tax support to avoid individual over-mechanization, to avoid the logic of unnecessarily frequent renewal of the fleet of machines, or to support the use of alternative fuel (both for the farmer and for manufacturers).

[47] Jeuffroy, M.H., & Salembier, C. (2021). Innovations couplées pour la transition agroécologique. Séminaire ACT-AgroEcoSystem.
[48] Huck, C., et al. (2024). Environmental assessment of digitalisation in agriculture : A systematic review. Journal of Cleaner Production, 472.
[49] La Rocca, et al., (2024). Estimating The Carbon Footprint Of Digital Agriculture Deployment: A Parametric Bottom-Up Modelling Approach. Journal of Industrial Ecology.
[50] FNCUMA (2024). Plaidoyer pour une mécanisation responsable, durable et vivable de l'agriculture française

- **Structural sobriety** will call upon different organizational methods, for example by taking advantage of the sharing and pooling of agricultural equipment (via Agricultural Equipment Use Cooperative).

These efforts at sobriety are obviously significant because they can introduce additional logistical constraints, especially since the time windows for action on agricultural routes are changing and will continue to change with climate change.

Quantifying technological effects is necessary to arbitrate the technological scenarios to be deployed. This is all the more important since the effects to be considered are sometimes multi-factorial and can be contradictory to each other:

- On the size of agricultural machinery for example, the wider and heavier the machines, the more efficient the efficiency per tonne of agricultural product transported or used, especially since the maneuvering times are reduced. With the increase in the size of agricultural machinery, we nevertheless take the risk of moving away from the versatility of certain agricultural equipment, to then enter into logics of specialization and optimization of the fleet from the point of view of energy consumption. The size of the machines will also impact soil compaction levels.

- On the energy mix of agricultural equipment, since 80% of plots are less than 1.5 km from an HTA (high voltage class A) network, we could predict an electricity supply for certain agricultural equipment (or robots) to avoid having oversized batteries. Methane tractors currently do not yet carry a full charge and it would be necessary to avoid trips to farm buildings or other recharging centers requiring too much energy. Very energy-intensive agricultural equipment (forage harvesters, combine harvesters) will most certainly not be able to switch to these energy substitution modes.

Rejecting agricultural equipment on the pretext that it is technological would be an ideological stance. In addition to the fact that equipment can be developed in very low-tech formats (see appendix – peasant agricultural equipment, for selective weeding or even direct seeding under cover), agricultural machinery has its place in supporting decarbonizing practices. For example, we will think of the technologies for burying nitrogen in certain agricultural equipment for nitrogen fertilization of plant production. **However, whatever happens, the deployment of technologies must be considered in a logic of sobriety so that their consequences do not add to the list of difficulties that the sector is already facing.**

D. Adopting a culture of precautionary principle to limit risks

Technological analyses must be dynamic and not static over time. We advise adopting a cautious stance and not making risky bets on the use and deployment of agricultural technologies, especially since we are not fully aware of the likely changes in our world, beyond a certain decrease in physical flows of materials and energy. Recent examples of overconsumption of electricity by large multinationals (and associated greenhouse gas emissions), notably Google and Microsoft[51], with regard to the deployment of artificial intelligence

[51] Le Monde (2024). Après Microsoft, Google voit ses émissions de CO_2 bondir à cause de l'IA.

(AI) technologies, with the resulting energy consumption and greenhouse gas emissions, suggest that these risks have not been adequately anticipated. To the extent that these artificial intelligence engines are also used in agriculture, even if to a lesser extent than in other sectors of the economy, these issues are particularly topical.

Each new development must be questioned in light of what a surplus of technology really brings. The gains in precision brought about, for example, by better spatial resolutions (finer pixels), temporal resolutions (more regular revisits) or spectral resolutions (finer information) of future Earth observation satellites (either by more precise satellites or by an increase in the number of satellites) should no longer be judged solely by the wealth of information they can provide but by a serious cost-benefit analysis, in particular by imagining how the response to this analysis is likely to evolve in the future.

Furthermore, it is common and plausible that a technology or a technological mix is not deployed under the conditions initially considered, and therefore ultimately have different effects. These risks of non-deployment are numerous and are not necessarily linked to a technological issue. Scaling up agricultural technologies can indeed be limited by, among other things (this list is not exhaustive):

- Infrastructural obstacles (for example, the required network architectures may not be available in rural areas),
- Obstacles to physical flows (there may be constraints on the type of energy available and its accessibility or supply to operate agricultural technologies),
- Organizational and/or skills obstacles (for example, with maintenance and repair pools for agricultural equipment not distributed across all territories),
- Regulatory obstacles (the movement of agricultural robots between plots is currently limited for safety reasons),
- Economic obstacles (the return on investment of the technology is not considered sufficiently interesting by field stakeholders), or
- Ethical obstacles (a technology is rejected by nature because it would challenge or transform the work of farmers too profoundly).

These risks are partly discussed in the matrices that we have proposed, but it is clear that a **detailed mapping of the risks of non-deployment must be carried out as soon as possible, in order to be able to navigate this uncertainty.** In particular, it will be necessary to ensure exit routes, for example by evaluating the levers (other technologies, organizational and sobriety levers, etc.) that can replace technologies that have not been deployed or for which deployment would go less well than expected. The concepts of technological lock-in and path dependency mentioned in this report make it possible to consider cases where we would commit too deeply to technological frameworks (a particular technology or a technological mix) without being able to go back and to question, in these cases, what would happen if constraints or shocks (financial, energy, etc.) were to knock on our door.

3. Cultivating heterogeneity

A. Equip all agricultural systems and not seek standardization

A technology supporting agroecology can be defined by its contribution to informing or controlling the processes that underpin the principles of agroecology[52]. Agroecological systems evolving in changing environments with high ambiguity and uncertainty are heterogeneous by nature. The agricultural technologies that will support them must exploit this heterogeneity not to standardize it but to exacerbate it[53]. This diversity, in a world under constraints, will provide more resilience to future shocks.

In the Shift Project scenarios and in the majority of scenarios proposed on a French scale (TYFA, Afterres, etc.), agricultural production systems remain diversified. **This culture of heterogeneity calls for properly equipping all sectors and production systems, some of which have been significantly forgotten or at least set aside**. We therefore invite to think broadly about the technological transfer of what already exists in certain sectors and to remobilize existing technologies and make them available and accessible for other sectors (organic farming, legumes, etc.). This adaptation is not easy and will require a powerful questioning of technology developers and existing institutions.

Organic farming systems or those that drive the implementation of agroecological practices (starting from incremental practices to transformative practices) often have more complex and diversified operating methods and multiple workshops. **Conventional technologies do not seem adapted to these routes which, unlike the relatively homogeneous systems of the dominant agricultural model, seek to cultivate their heterogeneity.** These diversified systems need to be supported throughout their production cycles in terms of planning with, for example, crop rotation and crop rotation simulators because the crop sequences are technical. Mixed crop-livestock systems, managing several workshops, need to have a panoramic view of their farm in terms of pasture, crop, and sectors.

Varietal selection and genome editing tools (markers and others) must be widely remobilized towards legume sectors (alfalfa, lentils, soybeans, etc.) to support the launch of these new sectors. Selection strategies will have to increasingly integrate notions around heterogeneity and diversity, not only at the individual level, but also at the level of the group of individuals that make up the plant cover or the herd[54]. There is also a particular issue around heterogeneity for legumes, which are called upon to grow mainly in the form of associated crops with cereals or grasses (in meadows) for reasons of economic balance and agronomic and nutritional complementarities.

The agricultural systems that we want to see come about must be supported, particularly because some can be time-consuming to manage. Some farms in agro-pastoral systems with

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52 Caquet et al. (2020). Agroécologie – Des recherches pour la transition des filières et des territoires. Chapitre 6 : Contribution des agro-équipements et du numérique à l'agroécologie. Renforcer la prise en considération du vivant. Edition Quae.

53 Zingsheim, M.L., & Doring, T.F. (2024). What weeding robots need to know about ecology. Agriculture, Ecosystems, and Environment, 364/

54 Gascuel-Odoux, C., et al. (2022). A research agenda for scaling up agroecology in European countries. Agronomy for Sustainable Development.

controlled release livestock have, for example, been very early in adopting GPS tracking to know where their animals are located, especially in rugged areas. Digital technologies can also be deployed to promote communication between peers, the sharing of good agroecological practices (because technical references are lacking), or the formalization of expert and local knowledge.

It will certainly also be necessary to prove both that agroecological practices have been implemented and that these practices have a real impact on the ecological transition of agrosystems. **Forms of performance obligations may be expected, justified by data collected and reported by agricultural technologies** (satellite monitoring, on-board sensors, etc.). The financing of these practices (payments for environmental services, sector bonuses or others) may be conditional on these performance obligations.

B. On the need for multi-scale reasoning

The transformation of the agricultural system leads to the development of sectors and production systems that, for some, are still largely in the minority in the agricultural landscape. For example, crop associations and legumes are more considered by organic farms and/or low-input systems. **Technologies could be seen as catalysts or facilitators of the movement to consider a scaling up of agricultural practices.**

These technologies, likely to support a shift to the next level, should not be proposed in a "one size fits all" logic but should be part of local dynamics and trajectories. A reorganization of agricultural landscapes, such as what The Shift Project advocates when it highlights an increase in mixed crop and livestock farming, could call for the spatial deployment of certain technologies that may not yet be available or only available in certain territories. An entire ecosystem may indeed be necessary locally (repairers and after-sales services, dealers, sectors and outlets, etc.) to allow certain technologies to land on the ground. Théo Martin explores, for example, the impact of milking robots at different organizational scales (farm, cooperation between breeders using or not using robots, maintenance basin within a network of agricultural dealers, etc.)[55].

The study of agricultural systems requires posing the issues at various spatial scales: plots, sectors, landscape, etc. Reasoning only at the plot scale amounts to reasoning in a vacuum, or at least in a fragmented way. Agricultural technologies can be used to take this step back. In the case of the study on the monitoring of pests/bioaggressors (see appendices), we shed light on the interest of digital technologies for dynamic and spatialized monitoring of bioaggressors at the territorial scale, in particular by combining connected traps, participatory approaches, data from connected weather stations or even satellite data.

In general, **it is clear that technological development remains concentrated at restricted spatial and temporal scales**, even though agroecological systems will depend more on neighborhood effects or landscape elements. These multi-scale approaches are all the more

[55] Martin, T., (2023). Les Sentinelles de l'Étable. Robotisation de la traite et nouvelle division du travail dans l'élevage laitier français. Thèse de Doctorat.

complicated since agroecological solutions are very much located in time and space, and therefore very dependent on local conditions[56].

4. Projecting future skills and jobs

A. New skills to develop

Agricultural technologies, if deployed, will require new knowledge and skills from the entire agricultural ecosystem[57,58].

Not all technologies require the same level of skills: some technologies will be used within the farm and will need to be mastered (digital technologies, robotics, etc.) while others will invest in the farm but will mainly require adapting agricultural practices (e.g.: varietal selection, new genomic technologies, biocontrol, etc.). More information-intensive technologies, which will generate more data or agronomic recommendations, will require more specific skills to understand the results obtained. This will perhaps be even more true in an agroecological transition context, where the need for new observations and knowledge is all the greater.

We can also expect that **the outsourcing[59] of so-called precision agriculture services, which is on the rise in France, will release the responsibility for skills development to other structures external to the agricultural farm.**

Agricultural advisors, as intermediaries in agricultural knowledge and advice networks, are an essential component of any agricultural innovation system[60,61]. The landing of agricultural technologies on the ground does not depend only on the farmer but on the entire ecosystem that gravitates around him. The agricultural advisor, too, must develop his skills to support, if it is deemed desirable, the deployment of agricultural technologies. Using the example of digital tools, advisors have the capacity to create hybrid knowledge where their knowledge of agricultural systems is combined with the results of digital tools. Advisors can then also play the role of intermediary between the farmer and digital technologies.

This development of skills must not be implemented without broader support for change. The introduction of technologies on farms cannot be considered as a simple addition of tools, all other things being equal. New roles are configured, new experiences are generated and the

56 Caquet et al. (2020). Agroécologie – Des recherches pour la transition des filières et des territoires. Chapitre 6 : Contribution des agro-équipements et du numérique à l'agroécologie. Renforcer la prise en considération du vivant. Edition Quae.

57 Chaire AgroTIC (2019). Se former au numérique. Quelles compétences acquérir pour les professionnels de l'agriculture ?

58 Vivea (2020). Quelles compétences pour une agriculture numérique ? https://vivea.fr/ressources/agriculture-numerique/

59 Nguyen, G. et al. (2020). "Strategic Outsourcing and Precision Agriculture: Towards a Silent Reorganization of Agricultural Production in France ?" ASSA-AAEA 2020 – Annual Meeting of the Allied Social Sciences Association and the Agricultural and Applied Economics Association

60 Aspexit (2021). Agriculture & Numérique : prenons-nous vraiment la bonne direction ? https://www.aspexit.com/agriculture-numerique-prenons-nous-vraiment-la-bonne-direction/

61 Eastwood, Callum, Margaret Ayre, Ruth Nettle, and Brian Dela Rue. 2019. "Making Sense in the Cloud: Farm Advisory Services in a Smart Farming Future." NJAS – Wageningen Journal of Life Sciences 90–91.

nature of relationships changes. The fact that agricultural technologies can deviate considerably from usual practices and generate uncertainties in the minds of advisors destabilizes or makes the roles and daily routines of the actors insecure, thus creating an impact on what they are and what they do. Agricultural advisors, by potentially moving from product promoters to service promoters (digital services, functional economy, etc.) must significantly change their messages and their ways of working. And these transformations are all the more necessary to support since the advisor has and/or will have additional responsibilities to consider around animal welfare, climate change or more broadly the deployment of agroecological practices.

B. Promoting interdisciplinary crossovers

Future innovations may not be so much technological but will rather come from the intersection of skills, between technologists, ergonomists, ecologists, designers, modelers, agronomists, geneticists, ecophysiologists, or even sociologists. We certainly do not yet know the complete ecosystem necessary to carry out innovative projects and our ideas are perhaps limited by an unknown disciplinary field. **The fact remains that a methodological framework is missing to work with skills from different disciplines.**

Interdisciplinary collaboration is easier said than done, especially since existing actors have more difficulty setting up transversal projects than within their own disciplines, or they are less valued in finding intersections with several themes than if they remain in their field of training. **These collaborations can be facilitated with common experimental platforms and central databases, interdisciplinary training and institutional cooperation and networks[62].**

C. Adoption of agricultural technologies on farms

The Great Farmers' Consultation[63], conducted in parallel with the work on Agriculture of the Shift Project, gave farmers the opportunity to discuss their positioning with regard to certain agricultural technologies. Even if the initial questions were quite vague[64] and focused on a few major categories of technologies (Precision Agriculture [Robotization, Digitalization], New Genomic Technologies), a diversity of responses emerged (respectively 50% and 30% for at least "Yes" or "Yes, I have already implemented it" for Precision Agriculture and New Genomic Technologies) **reflecting the different possible technological trajectories on agricultural farms. These varied orientations are a sign that, in the same way that agricultural production systems and greening pathways are multiple, technologization pathways cover a broad spectrum[65]**.

The adoption of agricultural technologies is a particularly complex process, dependent on cognitive structures (life history, agricultural objectives and preferences, etc.), social structures

[62] Storm, H. et al. (2024). Research priorities to leverage smart digital technologies for sustainable crop production. European Journal of Agronomy, 156.

[63] Grande consultation des agriculteurs, The Shift Project & The Shifters, Novembre 2024

[64] Question asked about agricultural technologies: Assuming that the practices below are financially profitable and that you have technical support, which practices would you like to implement?

[65] Schnebelin, Éléonore, Pierre Labarthe, and Jean-Marc Touzard. 2021. "How Digitalisation Interacts with Ecologisation? Perspectives from Actors of the French Agricultural Innovation System." Journal of Rural Studies. https://linkinghub.elsevier.com/retrieve/pii/S0743016721002205.

(collaboration networks, cooperatives, etc.), and physical structures (plot structure, location of the farm) in and around agricultural farms. The factors of technology adoption are often largely fragmentary and fail to account for the complex dynamics of technology adoption[66]. **It should be clear that it is not because a technology is not adopted that a farm should be considered behind in phase**. Non-adoption can be a completely reasoned choice that is part of a particular technological and operating trajectory.

To the extent that technologies will have to adapt to local contexts and conditions, it will be interesting to identify systems in transition[67], in the form of a hunt for innovations, in which agricultural technologies are used at a regular pace and integrated into the path of the farm.

[66] Pathak, Hari Sharan, Philip Brown, and Talitha Best. 2019. “A Systematic Literature Review of the Factors Affecting the Precision Agriculture Adoption Process.” Precision Agriculture 20(6): 1292–1316.
[67] Salembier (2021). Stimuler la conception distribuée de systèmes agroécologiques par l’étude de pratiques innovantes d’agriculteur.rice.s. Thèse de doctorat.

General conclusion

The development and deployment of technologies for decarbonization and adaptation of the agricultural sector must be planned over the long term, in line with the evolution of future agricultural systems. Initial "no regret" measures must be considered, leaving aside technologies deemed too risky or incompatible with the sector's decarbonization objectives, at least until a more in-depth analysis has been able to dispel these risks.

Agricultural technologies must be made more widely accessible, particularly in the least equipped technical and economic sectors that it seems desirable to support, by mobilizing and transferring technologies and resources (financial, organizational, etc.) from other well-studied agricultural systems (see the section of the report "Cultivating heterogeneity"). We must support collective approaches to openness, self-repair or open source (e.g.: Atelier Paysan[68], OS Farm[69], etc.), and limit the logic of patentability and monopolistic concentrations. These collective approaches will be all the more likely to land if interoperability standards and norms are actually followed. The question of the "commons" generated by agricultural technologies (digital data, resistant varieties, etc.) must be put on the table and well-educated.

Groups of technological actors must be supported, if they are able to demonstrate that they are able to assess the relevance of the technological solutions they support with regard to the transition of the sector as a whole. These inter-actor organizations must seek to diversify to promote cross-fertilization between different disciplines.

In this work, we have mainly proposed a dynamic reading of agricultural technologies in the sense that we have provided elements of discussion on the place of technologies to support the transition of the agricultural sector. **The question of whether these technologies will always have a place in an agriculture that has succeeded in transforming itself is also legitimate** (we could speak here of the place of technologies in cruising mode). If technological dependencies are still too strong in future agricultural systems, crises that could impact the functioning of technologies (flow disruption, energy limits, etc.) would have a cascading effect on our relationship with agro-ecosystems. We must therefore ensure that the resilience capacity of the agricultural system is at the heart of any decision to deploy technological innovation.

All these questions must be at the heart of French strategic plans (PARSADA, PLOAA, SNBC3, etc.) and priority research equipment programs (PEPR, French acronym) and the major associated challenges currently underway (PEPR Agroecology and Digital, PEPR Advanced Plant Selection, Major Biocontrol and Biostimulation Challenge, Major Robotics Challenge, etc.).

[68] https://www.latelierpaysan.org/
[69] https://www.osfarm.org/fr/

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Appendices

• Appendix 1 : Supplements on the methodology for constructing the technology panorama

The case of methane is thus removed from the matrix linked to plant production (even if we could still consider indirect CH_4 emissions via fuel production or certain agricultural productions such as rice growing). We have not broken down these matrices by sector, even if this more detailed work could have proven relevant. Some technical-economic orientations of farms are indeed much more equipped than others. **We are not submitting a matrix dedicated to mixed crop-livestock farming here.** As important as this technical-economic orientation is, it is clear that current agricultural technologies are primarily aimed at narrower sectors. We will have the opportunity to discuss this again later in the report.

The technological panorama proposed is relatively broad. However, it is certainly not exhaustive. The greatest difficulty in this work may have been to assign a coherent granularity both between categories of significantly different technologies but also in such a way as to make the mapping readable and actionable. **The work**, both that carried out with the working group and the workshops carried out in parallel, **demonstrated the heterogeneity of the vocabulary and technological representations of the participants. The definitions of the actors are not always common and certain terms are not always precisely defined.**

In order not to weigh down the matrices, the dimensions around the maturity and the capacity to deploy agricultural technologies in the field are not explained. These considerations are instead discussed for the technologies selected in the rest of the report. Representations in the form of Gartner curves or maturity, accessibility or deployability scales (TRL [Technology Readiness Level] or MRL [Market Readiness Level]) could be complementary to the matrices that we have proposed. An additional color scale to express these dimensions was not considered appropriate given the already large size of the matrices.

• Appendix 2 : Issue matrices and matrices of levers associated with technological innovations

These matrices complement the case studies given above.

A. Conventional selection

Technologies used (see overview): natural crossing or hybridization of the genetic material of a plant or animal, molecular marking, genomic selection

STRENGTHS	OPPORTUNITIES
• Conventional breeding offers proven	• The social acceptability of conventional

capabilities for massive mixing and blending of plants. • Conventional breeding offers the possibility of having mixtures of varieties or genotypes • Conventional breeding gives the ability to make selection adapted to the local soil & climate • Conventional breeding allows a gradual adaptation of plants to climate change (low delta) • Conventional breeding experiments are feasible on the farm • Breeding technologies require few additional cost structures (except for high throughput phenotyping) • Conventional breeding is effective in improving variety profiles, especially with modern methods (molecular marking, genomic selection, etc.)	breeding is facilitated compared to other genome editing approaches • There is a desire to push the development of legumes (not yet really covered by breeding)
WEAKNESSES • It remains difficult to select multi-dimensional criteria by projecting into future climate scenarios • There is a lack of research work on a whole bunch of plant species that are still too little considered • It is difficult to predict the behavior of a plant in a condition that has not been tested • Conventional selection can be time-consuming • Past selection work always leads to the use of phytosanitary products, but new directions (improved nitrogen use, disease resistance, etc.) are beginning to change this trajectory.	**THREATS** • Climate disruption is too fast compared to the deployment capacities of selection • There may be a risk of privileged interest for NGTs, without necessarily coupling with conventional selection • Phenotyping conditions are increasingly complex with climate disruption (with significant combinatorics..) • There may be a lack of outlets for the selected varieties (in agroindustrial systems for example) • We could become dependent on certain countries that would be the only ones to make productive cereals with the latest available technologies. • The potential of a variety is only revealed if the cultivation practices allow it

A matrix of action levers to exploit the strengths and opportunities of conventional selection while limiting the weaknesses and threats is presented below:

STRATEGIES FOR EXPLOITING OPPORTUNITIES THROUGH STRENGTHS • Drawing inspiration from adapted varieties/species developed in other countries • Developing new sectors/markets for legumes (and others) in France • Clarifying our food development objectives • Implementing participatory selection systems without cutting ourselves off from modern technological tools and the genetic variability developed by breeders • Setting sustainability and better nitrogen efficiency objectives for varieties	**THREAT PREVENTION STRATEGIES USING OUR STRENGTHS** • Massively develop seed sharing systems • Regulate seed exchanges • Create support mechanisms for the development of selection on protein species
STRATEGIES FOR EXPLOITING OPPORTUNITIES TO MINIMIZE WEAKNESSES	**STRATEGIES TO MINIMIZE POTENTIAL DANGERS AT THE INTERSECTION BETWEEN**

• Massively develop phenotyping on non-covered and orphan thematic crops • Put traditional selection at the service of future needs (90% of cultivated plants are non-irrigated, so there is a need to work on non-irrigation) • Orient conventional selection towards varieties adapted to increasingly drier conditions • Integrate resilience into the selected characteristics • Adapt varieties to low-emission cultivation practices (Soil Conservation Agriculture, direct seeding under cover)	**WEAKNESSES AND THREATS** • Organize citizen debates on the food transition

B. Peasant agricultural equipment for mechanical weeding

Technologies used (see overview): multi-use agricultural equipment (weeding, planting, harvesting, etc.), in the form of a bed, which can accompany agroecological practices (sowing under cover, etc.).

<table>
<tr>
<td>
STRENGTHS

Peasant agricultural equipment is generally lighter (less soil compaction)
This agricultural equipment makes it possible to reduce the arduousness of weeding work (especially if lying down...)
Peasant agricultural equipment is adapted to the farmer's working conditions
Peasant agricultural equipment can be retrofitted
This type of agricultural equipment maintains human work and agricultural employment
Peasant agricultural equipment is easily repairable
This agricultural equipment can be manufactured in self-construction (open source plans, sharing of experience). Self-construction is less expensive economically
There are extended communities to promote the exchange of good practices, improvement and repair of equipment
Peasant agricultural equipment can be multi-purpose (weeding, planting, harvesting)

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OPPORTUNITIES

Peasant agricultural equipment makes it possible to get away from the strong dependence on machine manufacturers in the world (see the market shares of agricultural equipment)
Peasant agricultural equipment offers the possibility of getting away from the dependence on materials and electronic components for classic agricultural equipment
This agricultural equipment contributes to the attractiveness of the agricultural profession thanks to the reduction of arduousness
This agricultural equipment can support the development of modest-sized structures and agroecologically intensive market gardening
This agricultural equipment can support the development of new cultivation routes that were too arduous
This agricultural equipment can support the development of diversified market gardening on a small surface

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WEAKNESSES

The construction and maintenance of this agricultural equipment can be time-consuming
Peasant agricultural equipment leads to a drop in yield per hectare and per person
This agricultural equipment is dependent on physical and material flows if electrically assisted
Farmers do not necessarily have the desire or shared will to self-build their equipment.

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THREATS

It may be difficult to deploy this type of agricultural equipment massively and in a limited time
Agricultural stakeholders could focus their interest on heavy agricultural equipment and robotics
The economic context that makes the workforce insufficient & the dependence on labor (foreign, interns, woofers, etc.) could lead to losing interest in this type of agricultural equipment
There is a prejudice of archaism of these agricultural equipment technologies. These tools are considered too uncomfortable
This agricultural equipment could be stacked with the agricultural equipment already present on the farm
The increase in the cost of food linked to the use of this type of agricultural equipment may not be accepted (cost of food which would increase)
Current tax and accounting policies push for the renewal of agricultural machinery

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A matrix of action levers to exploit the strengths and opportunities of peasant agricultural equipment while limiting weaknesses and threats is presented below:

<table>
<tr>
<td>STRATEGIES FOR EXPLOITING OPPORTUNITIES THROUGH STRENGTHS

● Produce comparative environmental and economic analyses between peasant agricultural equipment and conventional agricultural equipment
● Document / highlight the market shares, profits and turnover of the main agricultural equipment manufacturers
● Develop the equipment according to ergonomics (morphology, gender, etc.)
● Ensure sufficient feedback so that the tools evolve and improve</td>
<td>THREAT PREVENTION STRATEGIES USING OUR STRENGTHS

● Fund more widely the deployment or link with self-repair support structures (fab-lab, repair-café, other collective workshops)
● Direct direct financial aid (aid for the acquisition of equipment) and indirect aid towards this type of agricultural equipment
● Encourage agricultural employment and promote farmers' remuneration</td>
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<tr>
<td>STRATEGIES FOR EXPLOITING OPPORTUNITIES TO MINIMIZE WEAKNESSES</td>
<td>STRATEGIES TO MINIMIZE POTENTIAL DANGERS AT THE INTERSECTION BETWEEN WEAKNESSES AND THREATS

● Deploy training/awareness-raising on self-construction in farmers training courses and continuing education (agricultural high school, vocational baccalaureate)
● Propose hybrid models with semi-industrialized manufacturing (kit tools, etc.) according to open-source plans and specifications facilitating self-repair/adaptation
● Deploy test sessions, demonstrations, and introduction to tools at regional trade fairs
● Introduce farmers to this type of agricultural equipment more widely (trade fairs and others, etc.)</td>
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C. Electric robotics for selective weeding

Technologies used (see overview): lightweight robotic tool, powered by electrical energy, to ensure localized selective weeding. Several weeding methods are possible: UV, Thermal, Chemical, Mechanical, etc.

STRENGTHS	OPPORTUNITIES
• Some robots are lightweight (less soil compaction) • These robots make it possible to reduce the arduousness of weeding work • Weeding robots open up the possibility of doing organic farming without working the soil • Using a robot can free up working time for other tasks (for example, observing plots in parallel with robotic activities) • Robots can potentially work at any time of day • The French robotics sector is well developed • Regular passages of robots for weeding (mechanical or other) can limit resistance phenomena	• The difficulty in finding local and qualified labor can push to develop the robotics sector • The scarcity of fossil fuels and the difficulties of energy supply can guide towards light electric robots. • Robots can help increase the attractiveness of the profession for some young farmers • A Great Robotics Challenge[70] (PEPR AgroEcology & Digital) is underway • Agile and small robots can have a potential to promote the landing of agroecological trajectories • The use of robots can facilitate the deployment of agronomically advanced cultivation routes if selective weeding
WEAKNESSES • Weeding robots (and their on-board cameras) do not have the capacity to discriminate all species on the plots • The investment cost in robotic tools can be quite high • Robots are still very single-task (to be put into perspective on tool-carrying robots) • There are still very few life cycle analyses (LCA) on robotics (movement of robots between plots, lifespan of equipment, obsolescence, etc.) • The use of robots may require an additional need for skills to operate and repair the robots • The energy autonomy of robots is not yet clear (recharging batteries, connection to the network, etc.) • Robots are currently not yet fully autonomous (particularly for regulatory reasons) • Work flow rates vary between robots (potentially low) • Robots still have little capacity to work on large-scale crop systems • Robots need relatively easy field conditions to operate (no overly uneven terrain, etc.)	**THREATS** • Robots may require adapting crop routes to the operation of robots & standardizing agricultural routes • Farmers may not have the capacity to repair their work tools (user and operating licenses, new skills, etc.) • Robots can help replace farm workers • The purchase of robotic systems and the associated hidden costs (maintenance, updates, etc.) could increase the indebtedness of agricultural farms • Cyber-attacks on robotic units (hardware, firmware, communication systems) are possible. • The robot could be added to existing agricultural equipment and contribute to technological over-stacking. The acceptability of the agricultural environment and consumers of robotic routes to produce food is not guaranteed • We can expect inequalities of access to robotic tools in the territories (white areas, isolated farms, etc.) • Supply shortages of electronic chips could impact the robotics sector • The use of weeding robots could contribute to a loss of knowledge / empirical knowledge on local weeds • The data collected by the tools embedded in the robots could be captured by service providers and used for speculation on agricultural

70 https://anr.fr/ProjetIA-23-GDRA-0001

	commodities. ● Magnetic blackouts could affect the Global Navigation Satellite System (GNSS) positioning and operation capabilities of the robots

A matrix of action levers to exploit the strengths and opportunities of electric weeding robotics while limiting the weaknesses and threats is presented below:

STRATEGIES FOR EXPLOITING OPPORTUNITIES THROUGH STRENGTHS ● Prioritize the development of lightweight robots (e.g.: fleet of robots) ● Orient the development of robots to limit the arduousness of the work (follower robots, tool carriers, etc.) ● Develop multi-task robots	**THREAT PREVENTION STRATEGIES USING OUR STRENGTHS** ● Implement robot sharing models [limited due to low work flow] ● Support farmers in reorganizing their work around the robot ● Promote the development of open-source robotic building blocks ● Industrialize the deployment of robotic sectors to lower the price of robots ● Develop European electronic sectors to limit supply shocks (chips or others) ● Promote the development of algorithmic (AI) and open-source database building blocks
STRATEGIES FOR EXPLOITING OPPORTUNITIES TO MINIMIZE WEAKNESSES ● Supporting regulations to empower the action of robots in the field ● Increase the robustness/adaptability of robots in plots ● Force the development of robotic actions in agroecological itineraries	**STRATEGIES TO MINIMIZE POTENTIAL DANGERS AT THE INTERSECTION BETWEEN WEAKNESSES AND THREATS** ● Develop the electronics/robotics skills of farmers & dealers ● Raise awareness among consumers about the difficulty of manual weeding ● Find the right level of technology to limit the need for sensors/computing power ● Develop waste electrical and electronic equipment collection and recycling channels ● Encourage scalable, modular, repairable designs

D. Optimization of animal feed

Technologies used (see overview): Tools for modulating food rations (concentrates and others), Enteric CH_4 inhibitors, etc.

STRENGTHS	OPPORTUNITIES
• The GHG balance of livestock systems is quite clear (but not too much for co-products and mixed crop-livestock systems) • The individual identification of animals is relatively simple (passport and individual loop of animals even if everything is not necessarily connected) • We have access to massive and temporal data of animal states and consumption (but poorly for consumption in pasture) • The technologies are relatively mature and deployable • These technologies fit into an existing agricultural model for those who already use minerals and additives (more complicated for animals on grass) • The price of animal feed optimization technologies is not necessarily exorbitant for feeding technologies (additives and others) • There are quite a few technical references on the use of these technologies: publications on experimental farms, and close to field conditions	• The European Methane Pledge encourages interest in the subject of methane emissions. • Methane emissions in the agricultural GHG balance are very significant. • Agroindustries must be drivers in reducing their scope 3 and have an interest in turning to upstream methane emissions. • Reducing methane emissions could have the potential for financial and extra-financial valorization for struggling livestock sectors (sustainability and image) • Animal feed optimization technologies could help move towards better knowledge of continuous feed
WEAKNESSES	**THREATS**
• These technologies are mainly compatible with animals in buildings where the ration is controlled. • There is not always a clear economic model associated with these technologies (who pays...) • There are not enough reassurance factors (GHG and technical-economic references) • The ability of Cap2er methods (French carbon diagnostic for animal production) to precisely integrate all these feeding issues is not clear. • There may be possible contradictions between the GHG balance and animal welfare, or even broader life cycle analyses (LCA) • Some of these technologies may be incompatible with certain very demanding specifications • These technologies may carry a (low) risk of physical injuries • Some of these technologies may have antagonistic effects.	• These technologies could contribute to rebound effects due to feed efficiency (increase in the number of animals because of fewer emissions per animal) • There is a risk that these technologies will focus on intensive livestock systems and will not equip other animal sectors (risks of homogenization) • These technologies require a continued need for concentrated proteins and therefore call into question the origin of food and its overall balance sheet • These technologies could contribute to a tamagoshisation of animal production and reduce animal welfare to readily available observations • These technologies could divert agronomic issues to technological issues (do everything possible to avoid reducing livestock numbers) • The social acceptability of these tools is not guaranteed • A French meat consumption that does not decrease would require a shift to technological options and would not

	facilitate the reduction of the carbon footprint of livestock systems. France's dependence on meat imports (with a less clean GHG footprint than in France) could limit France's ability to reduce its GHG footprint • Efforts to reduce the GHG footprint of French livestock farming could be limited because this footprint is considered much better than elsewhere • Risk of not promoting the maintenance of permanent grasslands

A matrix of action levers to exploit the strengths and opportunities of animal feed optimization while limiting the weaknesses and threats is presented below:

STRATEGIES FOR EXPLOITING OPPORTUNITIES THROUGH STRENGTHS • Enriching the French Duralim charter on technological feed • Searching for genetic traits specific to methanogenesis for breed selection • Creating a link between the regulatory obligations of the sectors (intra and inter sectors)	**THREAT PREVENTION STRATEGIES USING OUR STRENGTHS** • Provide technical and financial support to breeders in their decarbonization strategies • Develop local plant sectors to limit dependencies on distant protein feed • Experiment on avant-garde pilot farms & on marginal breeding systems • Implement multi-scale strategies to avoid losses/gains at different scales
STRATEGIES FOR EXPLOITING OPPORTUNITIES TO MINIMIZE WEAKNESSES • Recommend decarbonizing technologies to certified references in specifications • Set up emission ceilings per cow or system and do not report everything to the surface area or unit produced • Continue to develop technical and economic benchmarks in real conditions	**STRATEGIES TO MINIMIZE POTENTIAL DANGERS AT THE INTERSECTION BETWEEN WEAKNESSES AND THREATS** • Establish pasture access obligations for livestock sectors

E. Production in controlled environment

Technologies used (see overview): Technological systems for production in a controlled environment, serving several different production models (aquaponics, hydroponics, etc.)

STRENGTHS	OPPORTUNITIES
• These technologies allow intensive production on a small surface area • These technologies allow significant savings on certain inputs (particularly phytosanitary products and water), better circularity and looping of inputs • The plants are less subject to disease, even if they are replanted afterwards • These technologies have the potential to bring urban dwellers closer to production • There are many different models of production in a controlled environment (aquaponics, hydroponics, etc.) • These technologies have little seasonality and can therefore allow for the hiring of labor on long-term contracts.	• These technologies have the potential to limit imported deforestation by producing certain products directly on site. • These technologies have the potential to reduce avoided emissions (e.g.: avoiding using mangroves for shrimp farming) • Local production in a controlled environment could reduce or limit dependencies on other countries (e.g.: laws passed by India and Morocco or export limitations) • These systems offer the possibility of seeking out old genetics or specific varieties (which would be too sensitive in production outside) • The strong constraints imposed on input consumption (e.g.: Barcelona on water) can push to develop this type of technology • The risks of water shortage (greater than heat risks) can call for developing this type of economical technology.
WEAKNESSES	**THREATS**
• Production with these systems is often constrained for certain crops (cereals, etc.) • These production systems are difficult to scale up • These technologies do not necessarily respond to a food security issue because few calories are produced (but free up space and agricultural areas)	• Competition is possible with open-field feeding • These technologies can completely automate production systems and impact associated agricultural employment. • A risk of concentration of actors on macro-farms in controlled production is possible (identical risk for current agriculture) • The origin of the feed of livestock (aquaculture and others) for certain controlled production systems is questionable • The social acceptability (farmers and consumers) of production in a controlled environment is not guaranteed

A matrix of action levers to exploit the strengths and opportunities of controlled environment production while limiting weaknesses and threats is presented below:

<table>
<tr>
<td>STRATEGIES FOR EXPLOITING OPPORTUNITIES THROUGH STRENGTHS

● Promote the controlled production of species sensitive to climate change
● Maximize genetic diversity in greenhouses
● Facilitate the installation of greenhouses in urban and non-habitable areas
● Do not limit vertical agriculture to an urban problem</td>
<td>THREAT PREVENTION STRATEGIES USING OUR STRENGTHS

● Financially support local production (especially those that avoid imports)
● Set up intra- and inter-sector cooperation systems between conventional and greenhouse systems
● Facilitate the installation of these systems in places where the conventional agricultural model is struggling</td>
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<td>STRATEGIES FOR EXPLOITING OPPORTUNITIES TO MINIMIZE WEAKNESSES

● Use greenhouses to test the adaptation of crops to additional stresses
● Carry out complete Life Cycle Analyses [LCA] (particularly energy) of these types of production
● Disseminate more widely the LCAs already carried out</td>
<td>STRATEGIES TO MINIMIZE POTENTIAL DANGERS AT THE INTERSECTION BETWEEN WEAKNESSES AND THREATS

● Raise awareness and make known the origin of the products currently consumed
● Organize visits to production sites in a controlled environment</td>
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F. Digital monitoring of pests on a territorial scale

Technologies used (see overview): connected traps, connected weather stations, participatory approaches (crowdsourcing), satellite technology, etc.

STRENGTHS	OPPORTUNITIES
• These monitoring technologies focus on prevention and the exchange of best practices • These technologies can operate using low-speed and low-tech networks (low-speed satellite is also arriving) • The spatial coverage allowed by these monitoring technologies is significant • Connected trapping is more qualitative (with dynamic and frequent surveys) than manual trapping • Trapping tools are financially affordable for agricultural stakeholders • Traps and weather stations can be deployed quickly on a large scale (but it is difficult to deploy a dense network)	• New pests are likely to arrive in our territories and will need to be monitored. • The distribution areas of insects (migratory insects and other insects) will evolve and will need to be better characterized. • There is an interest in the knowledge and observation of certain insects. Need for regular monitoring because knowledge can become obsolete over time. • The reduction in the supply of pesticides and the power of the chemical solutions used will require a more detailed knowledge of pest monitoring. • The digitalization of traps encourages an interest in trapping • Feedback is already available with the networks of traps and weather stations installed • The creation of strong links between different actors in the territory is important. The use of these monitoring tools could help to promote this link.
WEAKNESSES	**THREATS**
• The use of these tools for territorial monitoring requires strong involvement of participants. Need for a network of actors accustomed to collective monitoring • There may be limits in the transferability of forecasting models to different spatial scales • Trap networks are currently not dense enough to carry out spatial monitoring • The data from these monitoring tools may have biases (of several types). Artificial intelligence tools (in connected traps for example) have the capacity to limit biases and filter human diagnostic errors. • The data is sometimes collected at scales that are sometimes too large (and not necessarily exploitable) which do not allow decision-making. • Knowledge on the development of pest outbreaks and insect population dynamics is limited • There is a lack of entomologists and detailed knowledge of insects • The quality of weather predictions in the medium / long term may be limited • Consent to share data on this type of collaborative monitoring technology may be limited.	• There is a risk of unequal participation in the territory and therefore of a loss of momentum for some of the stakeholders involved (especially if some stakeholders consider that their pest risk is low). • Stakeholders could have bad intentions in using the data (questioning the ownership and sharing of the data) • These monitoring tools could compete with existing tools (such as the Plant Health Bulletin or other) or with stakeholders with divergent interests. • Current tools do not offer a prescription for action after insect detection because it is too risky and due to a lack of skills among digital tool providers. • There is a risk of directing the tools towards certain pests rather than others (for financial or other reasons). •

A matrix of action levers to exploit the strengths and opportunities of pest monitoring technologies on a territorial scale while limiting weaknesses and threats is presented below:

STRATEGIES FOR EXPLOITING OPPORTUNITIES THROUGH STRENGTHS • Implement nudges to promote good practices (and would indirectly reduce Treatment Frequency Indices or other) • Fund territorial engineering positions / Facilitators • Create synergies between sectors / territories. • Define frameworks for inter-stakeholder collaboration in the territory (Plant Health Bulletin in France, Regional Directorate for the Environment, Planning and Housing in France,, etc.). Identify the stakeholders who could play the role of coordinator • Create dynamic and accessible spatio-temporal maps of pest developments • Facilitate the collection of trap data (e.g. via crowdsourcing or via operators in the field)	**THREAT PREVENTION STRATEGIES USING OUR STRENGTHS** • Launch financial incentives for stakeholders to participate in trap networks • Demonstrate the interest in collaborating between stakeholders (e.g. Centipede) and question the interests of each of the stakeholders in place (look for intersections or overlaps of interests) • Put Plant Health Bulletin data in Open Data, and in spatialized form • Define the framework for sharing data and question the type of data that should be seen as "common". • Facilitate the self-construction of connected traps.
STRATEGIES FOR EXPLOITING OPPORTUNITIES TO MINIMIZE WEAKNESSES • Mapping sites at risk of pest development following climate change • Improving the multi-species detection capabilities of traps and models • Increasing the pool of entomologists in Agritech tool research and development teams • Improving the modeling of pest development with climate change (and developing models because they are based on old climate contexts)	**STRATEGIES TO MINIMIZE POTENTIAL DANGERS AT THE INTERSECTION BETWEEN WEAKNESSES AND THREATS** • Consider the number of sensors and IT architectures to limit the total carbon footprint of monitoring • Massively deploy low-tech sensors.