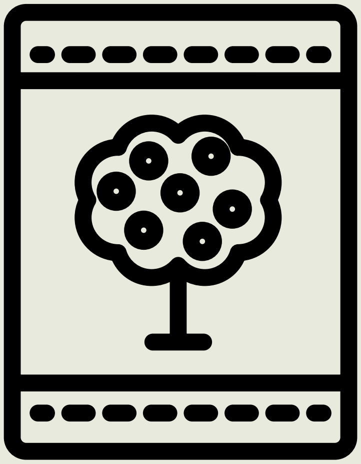
Global Innovation Needs Assessments

Decarbonizing agrochemical inputs

November 1, 2021



Funded by:

climateworks FOUNDATION

Foreign, Commonwealth & Development Office

Analytical support from:

:vivideconomics

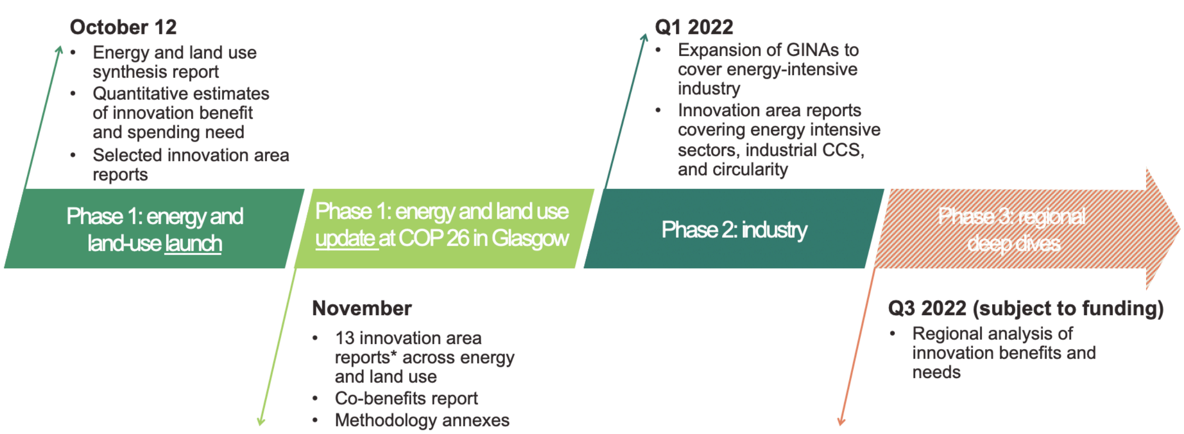
The findings and views expressed across this project do not necessarily reflect the views of ClimateWorks Foundation, the Government of the United Kingdom, or Mission Innovation

The Global Innovation Needs Assessments

The Global Innovation Needs Assessments (GINAs) is a first-of-its-kind platform for assessing the case for low-carbon innovation. The GINAs take a systemwide perspective, explicitly modeling the impact of innovations across the global economy. Uniquely, the analysis quantifies the economic benefits of low-carbon innovation and identifies the levels of public investment—from research and development to commercialization—needed to unlock these benefits. The analysis is divided into three phases: Phase 1, global energy and land use; Phase 2, global industry; and Phase 3, regional deep dives. This report is part of Phase 1's investigation of innovative technologies in the energy and land systems.

The analyses do not assess all relevant technologies, nor do they evaluate all relevant factors for policy judgments. Instead, the work is intended to provide a novel evidence base to better inform policy decisions. The Phase 1 analysis looks across a broad range of climate mitigation technologies in energy and land use, including demand response to protein diversification, to model the economic value of related innovation investment. Later phases expand the research. As with adoption of all technologies, including some controversial ones described in this report, there are risks and potential downsides. Technology investment is ultimately a policy judgment. This analysis provides no policy recommendations for that investment.

Phases of the Global Innovation Needs Assessments



The Global Innovation Needs Assessments project is funded by the ClimateWorks Foundation and the UK Foreign, Commonwealth & Development Office. Analysis was conducted by Vivid Economics. Thank you to the UK Department for Business, Energy and Industrial Strategy (BEIS) analysts and the Mission Innovation Secretariat, which were consulted on aspects of the work, and for BEIS support for the 2017–2019 Energy Innovation Needs Assessments, which developed the methodological approach taken here.

The findings and views expressed here do not reflect the view of ClimateWorks, the Government of the United Kingdom, or Mission Innovation.

Phase 1 GINA outputs

The suite of reports across innovation areas methodological annexes and a synthesis report for GINAs are available on the GINA website at https://www.climateworks.org/report/ginas/.

The suite of outputs for Phase 1 of the Global Innovation Needs Assessments

1. **Energy and land use synthesis report: slide-based summary for policymakers and executives**
   Synthesis of the findings across the innovations considered in energy and land use
2. **Innovation reports** – in depth quantitative analysis for industry and policy analysts

Energy

- **Wind power** Offshore and onshore wind turbines
- **Low carbon hydrogen** Electrolyzers and gas reforming with CCS
- **Solar power** Utility-scale and distributed PV
- **Low carbon fuels** 2nd generation biofuels, synthetic fuels (H_2 + CO_2)
- **Nuclear power** Small modular and large-scale advanced reactors
- **System flexibility** Battery storage, power-to-X, demand response
- **Buildings** Heat pumps, building fabric
- **Power CCS** CCS in power generation (coal, gas and biomass)
- **Zero-carbon road transport** Battery electric vehicles, fuel cell electric vehicles

Land use & agriculture

- **Protein diversity** Novel protein-rich food and feed
- **Decarbonizing agrochemical inputs** Innovative fertilisers and pesticides
- **Yield enhancing technologies** Digital agriculture and vertical farming
- **Irrigation** Improved irrigation methods and systems

The selected innovation areas were selected for their potential for further innovation and the potential magnitude of the associated system benefits. Their selection here is because they could play a key role in a net zero pathway but does not imply that an optimal net zero pathway necessarily includes them. Further notes on the rationale behind their selection is provided in the methodology annex on the GINA website

3. **Co-benefits of innovation report** – qualitative analysis of the environmental and other non-economic benefits of net-zero innovation
4. **European case study** – analysis of jobs and growth benefits in Europe specifically
5. **Methodology annex** – description of the modeling approach

Executive Summary

A transition away from traditional synthetic fertilizers and pesticides offers vital opportunities to decarbonize the agriculture and food system. There are two main areas of innovation:

- **Organic products**: Fertilizers and pesticides can be derived from microbes, animal waste, plant waste, and other natural sources.
- **Low-carbon synthetic products**: Advanced technologies such as nano structures can be used to improve the nutrient use efficiency (NUE) of synthetic fertilizers.

Increased use of innovative synthetic and organic fertilizers and pesticides in the agriculture system could reduce the cost of climate mitigation by US$521 billion by 2050. Displacing the use of traditional synthetic products will—when combined with spatial planning—decrease emissions from these products' production, transportation, and application. In addition, the increase in yield resulting from innovation can reduce pressures on land use, avoiding deforestation and biodiversity loss. The reduced use of traditional synthetic products is also expected to reduce pollution and agricultural runoff with improved outcomes for biodiversity, although trade-offs exist. Other promising innovations that could help decarbonize the industrial production of agrochemical inputs will be covered in Phase 2 reporting.

Major socioeconomic benefits could be delivered if the potential of innovative synthetic and organic fertilizers and pesticides is realized. Under a scenario of rapid deployment of organic products and nano structures, the grossed value added (GVA) by the switch to organic inputs and nanotechnologies is expected to increase by 8.4% per year, reaching US$59 billion in 2050. The transition is also expected to create 262,000 additional jobs, supporting 304,000 jobs in total.

To realize the full benefits of innovative synthetic and organic fertilizers, public spending and RD&D and commercialization will both need to increase to US$500 million per year. Targeted public efforts are required to accelerate farmers' uptake of organic and innovative synthetic fertilizers and pesticides. High upfront costs, information gaps, regulation, and consumer acceptance are currently hindering the shift away from traditional synthetic products. Public support should focus on addressing these barriers so that the private sector can invest with greater confidence and at a lower cost. Supporting knowledge diffusion is of particular importance because it is likely to encourage the adoption of new technologies among farmers and to increase acceptance among consumers.

1. Uptake of agricultural inputs

The role of fertilizers and pesticides

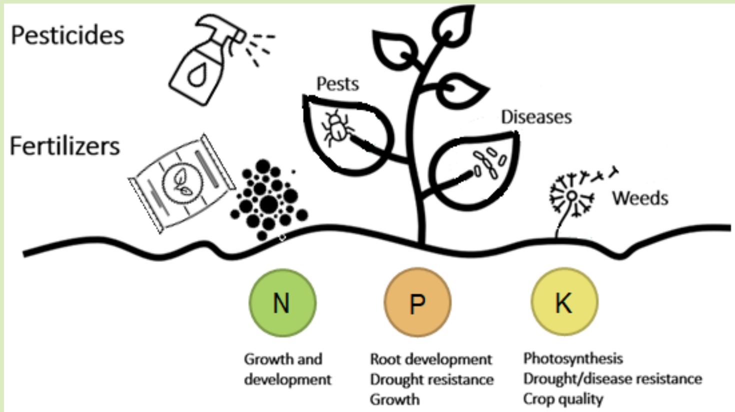
Crop nutrition and protection play a crucial role in global food systems, supporting higher crop yields and, therefore, helping the agricultural sector meet the needs of a growing population. Fertilizers and soil additives are used to supply nutrients and improve the physical properties of the soil, whereas pesticides are used to protect crops from weeds, pests, and diseases. Together, these agricultural inputs have boosted the production of food, feed, fiber, and biofuel to the extent that nitrogen fertilizer supports half of the global population (Erisman et al. 2008).

Although agricultural inputs help boost yields, thereby potentially sparing land for nature, their production, transportation, and application have resulted in substantial environmental damage. By increasing crop yields, agricultural inputs reduce agricultural land use pressure and increase land use options, including restoring natural habitats and nature-based solutions, thereby sequestering carbon and reducing net greenhouse gas (GHG) emissions. Production of agricultural inputs is a major source of GHG emissions, in particular, nitrous oxide, which accounts for roughly 4% of annual GHG emissions (IPCC 2014). One of the key inputs for nitrogen fertilizers, ammonia has a high energy intensity, and it accounts for 1.3% of global energy consumption (International Energy Agency 2021). Pesticides release negligible GHG emissions, but they may leach into the soil, end up in groundwater or other water bodies, or dissipate into the air, polluting ecosystems and harming human health.

Fertilizers and pesticides

Fertilizers are both organic and synthetic substances, composed of chemical elements, that serve to supplement soil nutrients and minerals. Nitrogen (N), phosphorous (P), and potassium (K) are the main nutrients in all fertilizers. Each one has a specific and essential function that cannot be replaced. Nitrogen serves as the main constituent of most fertilizers, supporting growth, development, and yield. Phosphorous is crucial for root development, strengthening a plant's drought resistance as well as broader growth activities. Potassium is central to photosynthesis and contributes to crop quality and resistance against disease and drought. Aside from the three main nutrients, micronutrients such as sulphur, magnesium, and calcium support the various processes of crop growth and development.

Pesticides are organic or synthetic substances that prevent, destroy, repel, or mitigate the harm caused by weeds, pests, and diseases that exist in natural ecosystems. Pesticides include insecticides, herbicides, fungicides, disinfectants, and repellents. Of the market for pesticides, 47.5% of products are herbicides, 29.5% are insecticides, 17.5% are fungicides, and the remaining 5.5% encompass other pesticides. Pesticides are considered most effective when used in conjunction with integrated pest management systems, combining pesticide application with strategies for pest identification, trapping, and targeting.



Demand for novel inputs is driven by the need to meet increasing global food demand while also reducing the impacts of agriculture on the natural environment. Table 1 presents an overview of the different types of currently available agricultural inputs, which includes organic and novel synthetic inputs.

A switch to organic fertilizers and pesticides can offer a lower energy option to synthetic products. Organic fertilizers and pesticides are derived from natural sources, including microbes, animal waste, and plant waste, and their production processes tend to be less energy-intensive, lowering GHG emissions. In addition, if stored and managed appropriately, these fertilizers and pesticides can result in less environmental harm.

Innovation in synthetic products also offers the opportunity to reduce the environmental impact of existing technologies and to enhance efficiency. Synthetic fertilizers with a higher NUE reduce the amount of excess nutrients that disperse into the environment, thereby reducing the impact on biodiversity. Nanotechnologies are especially effective in improving the NUE of agrochemicals by exploiting the nanoscale porous domains on plant surfaces. Other technologies, such as enhanced efficiency fertilizers (EEFs) also demonstrate significant environmental benefits. EEF use reduces N_2O emissions by up to 62% relative to more traditional fertilizers (Halvorson et al. 2014).

Table 1. Innovation in agricultural inputs

Product	Synthetic/ organic	Description
Holobiomics	Organic	Use of soil organisms can enhance ecosystem service delivery, including plant nutrition, through the promotion of soil biodiversity and targeted management of soil community composition.
Soil additives	Organic	Soil additives, such as biochar or compost, can optimize water use or increase soil fertility. They can be used to assist plant growth in infertile environments.
Microbials	Organic	Microbial inoculum or extracts can increase plant nutrient uptake, reduce disease incidence, or stimulate growth.

Botanicals	Organic	Pesticides and fertilizers can be made from plant extracts such as bark.
Macrobials	Organic	Macrobials are insects, mites, and entomopathogenic nematodes that can be used to control pests, reducing the need for synthetic pesticides.
Nanotechnologies	Synthetic and organic	Nanostructures can be used to deliver fertilizers and pesticides to the agricultural system. Nanoparticles have a high surface area and high sorption capacity and their release can be directed to targeted sites, making them a part of a “smart delivery system.”
Enhanced efficiency fertilizers	Synthetic	These fertilizers are smart-controlled released to meet the needs of the root/plant stage.

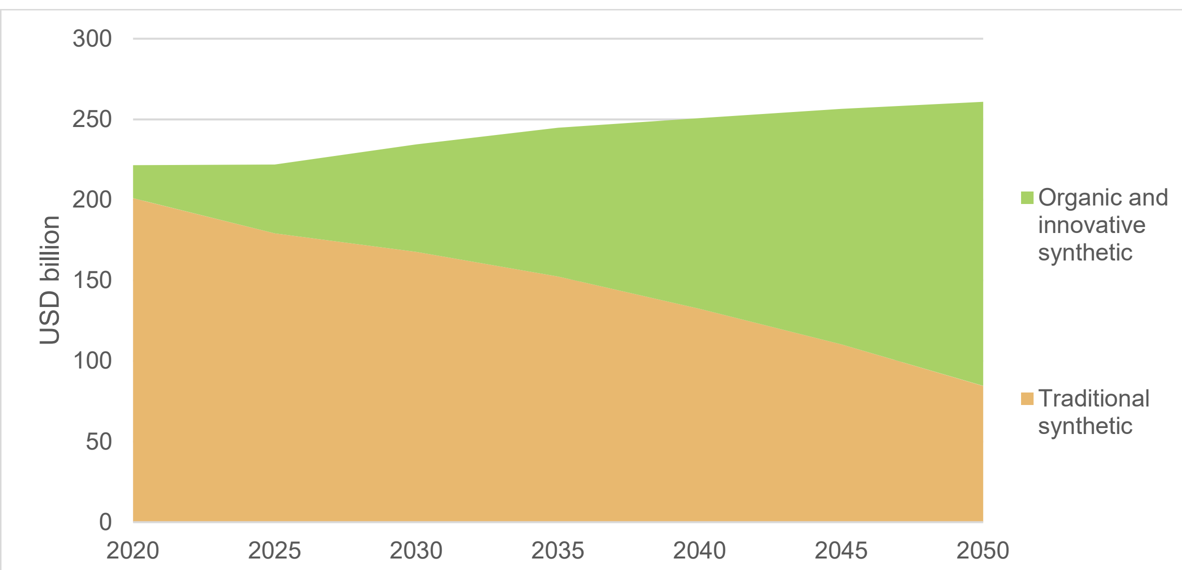
Source: Vivid Economics based on Herrero et al. (2020).

Future role and deployment potential

Population growth and economic development are placing significant pressure on agriculture systems. Population growth, in conjunction with economic development, is expected to increase demand for food by 62% to 98% between 2005 and 2050 (Valin et al. 2014). Future urban expansion is expected to occur largely in cropland areas, reducing the global cropland extent in 2030 by some 2% relative to 2000 (d'Amour et al. 2016). Given these trends, intensification of agricultural production in existing areas is key to meeting the increasing demand for food. Growth in agricultural yields is expected to come, in part, from increased application of fertilizers, pesticides, and soil additives, raising both GHG emissions and pressure on natural ecosystems. Modeling by Vivid Economics suggests that under a low-innovation scenario, demand for fertilizers and pesticides can be expected to grow by 43% by 2050.

To enable sustainable intensification of agricultural systems, innovation in agricultural inputs is critical. Innovations in both organic and synthetic products will help increase crop yields while minimizing the environmental impact of agricultural production (Muller et al. 2017). The market for novel agricultural inputs remains small at about US$30 billion compared with conventional markets, which currently stand at some US$220 billion and which are dominated by traditional synthetic products. However, if global warming is to be limited to 1.5°C, the market for organic and innovative synthetics must grow rapidly over the next few decades. Modeling by Vivid Economics suggests that under a high-innovation scenario, sales of innovative synthetic and organic products could increase to US$118 billion by 2040 (see Figure 2), with traditional synthetic products decreasing to less than half of the total market.

Figure 1. Decreasing market value of traditional synthetic fertiliser and pesticides in the high-innovation scenario.



Source: Vivid Economics.

2. Innovation opportunities

Cost and deployment barriers

The farming skills and knowledge needed to apply organic fertilizers and pesticides inhibits those inputs' adoption (Case et al. 2017). Application rates of synthetic fertilizers and pesticides are readily defined, but the exact nutrition ratio of organic products can be uncertain because of their limited track record across a diversity of local conditions. In addition, because nutrients stay in their natural form, organic products can be more demanding in terms of soil requirements and application timing than synthetic products. Adoption of innovative inputs requires strong agricultural extension programs to overcome these barriers and to support the transition from conventional inputs.

Logistics and infrastructure also inhibit the commercialization of organic products (Sustainable Food Laboratory 2014). Farmers can be reluctant to use organic inputs like animal manure or compost because some of these inputs are associated with strong odors and may have handling or storage requirements to prevent biological contamination. Moreover, identifying and establishing stable relationships with suppliers of organic products can be difficult because these suppliers are often small, widely scattered farmers. In addition, current regulations limit international trade in waste-based products, which further limits supply.

Commercialization of innovative synthetic pesticides and fertilizers is slowed by high investment costs. Use of innovative agrochemicals could minimize synthetic fertilizer and pesticide runoff while increasing crop yields. By increasing the precision with which synthetic products are applied to crops, nanotechnologies and increased-efficiency agrochemicals could reduce the amount of these products that is required, thus reducing production costs. However, the upfront investment costs associated with all synthetic agrochemical inputs, including research, development, and manufacture, are generally high, which means commercialization of innovative products has been a slow process.

In Europe, nanomaterials and other input technologies are subject to stringent risk assessment, regulation, and authorization, which can slow delivery of these innovations to market. Several countries are examining the appropriateness of their regulatory frameworks for dealing with nanotechnologies. The European Union, along with Switzerland, is the only world region where nano-specific provisions have been incorporated in existing legislation. Technologies approved for farming in some countries may not be approved in others, potentially leading to trade barriers. Although regulators need to continue to balance the benefits of new products against potential harms, harmonizing legislation on nanomaterials and other input technologies would encourage knowledge sharing among countries as well as advance technological innovation.

Key innovations

Collaboration among businesses, researchers, and farmers could facilitate development and adoption of novel inputs. This collaboration would integrate input from end users, increasing the likelihood of uptake, and it could even spur creation and implementation of a business model for the innovation once developed.

Innovation in waste-based fertilizers processing could increase the nutritional value of crops (Jensen et al. nd**).** Organic fertilizers can be processed so that unwanted chemical substances are eliminated, and desirable nutrients are kept. This processing can enhance the nutritional value of organic products, driving potential market premiums (Case et al. 2017).

Advancements in manufacturing processes for nanomaterials are needed to reduce costs and increase commercialization. Nanomaterials are currently expensive to manufacture, limiting their adoption. Significant investment in scaling up manufacturing of nanotechnologies has the potential to substantially reduce the nanotechnologies' cost, enabling precision use of fertilizers and pesticides.

Concentrated efforts to improve the regulatory environment could help to integrate novel technologies into farming practices. In Europe, nanomaterials and other input technologies are subject to a stringent regulatory environment, which is a fundamental barrier to market entry. Therefore, further research is needed to highlight the benefits of these technologies and to mitigate concerns about their potential risks. Once there is an evidence-based case for such technologies, regulation of their use can be fitted for purpose.

Policy innovation is needed to improve the cost competitiveness of new input technologies. Existing subsidy systems often do not reflect the externalities of pollution from the use of conventional inputs. Reflecting the cost of emissions damages from inputs and supporting payments for carbon sequestration in soils, for example, would help support the business case for novel inputs.

3. Benefits of innovation

Climate benefits

Achieving net-zero targets will require significant reductions in emissions from both the energy and the agricultural sectors, with any remaining hard-to-abate emissions offset by carbon removals in the short and medium terms. Carbon sequestration in forests and peatlands and other nature-based solutions is not sufficient to offset current emissions from the agricultural sector. Moreover, the land sector is being called on to offer negative emissions to offset persistent emissions from the energy sector. Simply put, technical innovation in the agricultural sector is critical to achieving climate targets.

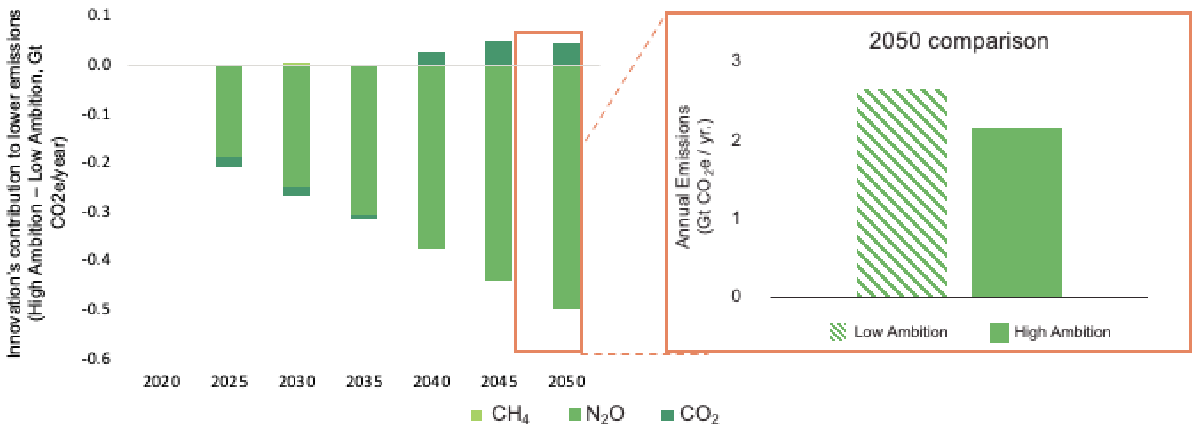
By reducing emissions from agriculture and enhancing carbon sequestration of the land use sector, innovative agricultural technologies can reduce the overall cost of mitigation. Innovative agricultural technologies can both reduce emissions in the land use sector and make land-based offset strategies less expensive, reducing the need for ambition in the energy system to stay within the emissions budget associated with a given climate target. This climate benefit, or net reduction in costs across the energy and land systems resulting from aggressive RD&D and commercialization of agricultural innovations, is what this work attempts to estimate. (Other benefits of agricultural innovations, such as positive impacts on health and biodiversity, are analyzed in a separate report.)

In the context of this report, the climate benefit is calculated as the difference in the total system costs of a high-innovation scenario and those of a low-innovation scenario, whereby

- **System costs** are all capital, operating, and fuel costs within the global energy system
- **Low-innovation scenario** represents market-driven progress in the absence of public sector support
- **High-innovation scenario** represents progress driven in part by government support of RD&D and deployment (i.e., commercialization) that accelerates cost reductions.

Uptake of organic and innovative synthetic fertilizers and pesticides could yield US$521 billion in climate mitigation benefits by 2050. A growing market for these products would reduce GHG outputs, reducing N_2O emissions by 19% relative to a low-innovation scenario. Because innovative fertilizers and pesticides lead to higher crop yields, they reduce the need to apply less efficient agrochemicals to wider land areas, which helps reduce both GHG emissions and land use pressures.[1] The climate benefits of investing in agricultural input innovation could be larger if the potential of low-carbon ammonia is unlocked through cheaper, widely available low-carbon hydrogen. The GINAs *Low-Carbon Fuels* report discusses innovations in energy provision that could help support decarbonization, and Phase 2 of GINAs will cover innovation in the industrial sector.

Figure 2. Annual emissions decline in the high-innovation scenario in agricultural inputs.



Source: Vivid Economics.

Innovative low-carbon agrochemicals are expected reduce environmental impacts. Synthetic fertilizers have played a significant role in enhancing agricultural yields, but they have also been a major driver of environmental pollution and climate change. For that reason, nano fertilizers and similar nano-technologies are being developed to encapsulate plant nutrients within nanomaterials, which can then be delivered in the form of nano-sized emulsions. Nanomaterials help increase crop yield by regulating the delivery of nutrients, thus increasing NUE and improving the nutritional quality of field crops (Iqbal 2019).

Human health and nature benefits

Aside from reducing GHG emissions, innovative input technologies can provide benefits to nature. The application of fertilizers and pesticides has been associated with big decreases in biodiversity. Runoff has led to coastal eutrophication and creation of more than 400 hypoxic zones covering more than 245,000 km^2 of ocean area (Diaz and Rosenberg 2008). By reducing soil degradation and chemical runoff, innovation in input technologies will reduce biodiversity loss and help maintain ecosystem services. Furthermore, increases in crop yields due to application of innovative fertilizers and pesticides will reduce the risk of deforestation. A switch to innovative fertilizers and pesticides could also

[1] Higher crop yields and innovative fertilizers and pesticides tend to reduce the amount of land required for agriculture and thus increase land available for nature and other uses.

bring benefits for human health. Vivid Economics estimates that average crop prices will be 6% lower globally by 2050 in a high-innovation scenario, compared with a 1.5°C future with lower agricultural efficiency. The decrease in prices will increase food security and reduce malnutrition.

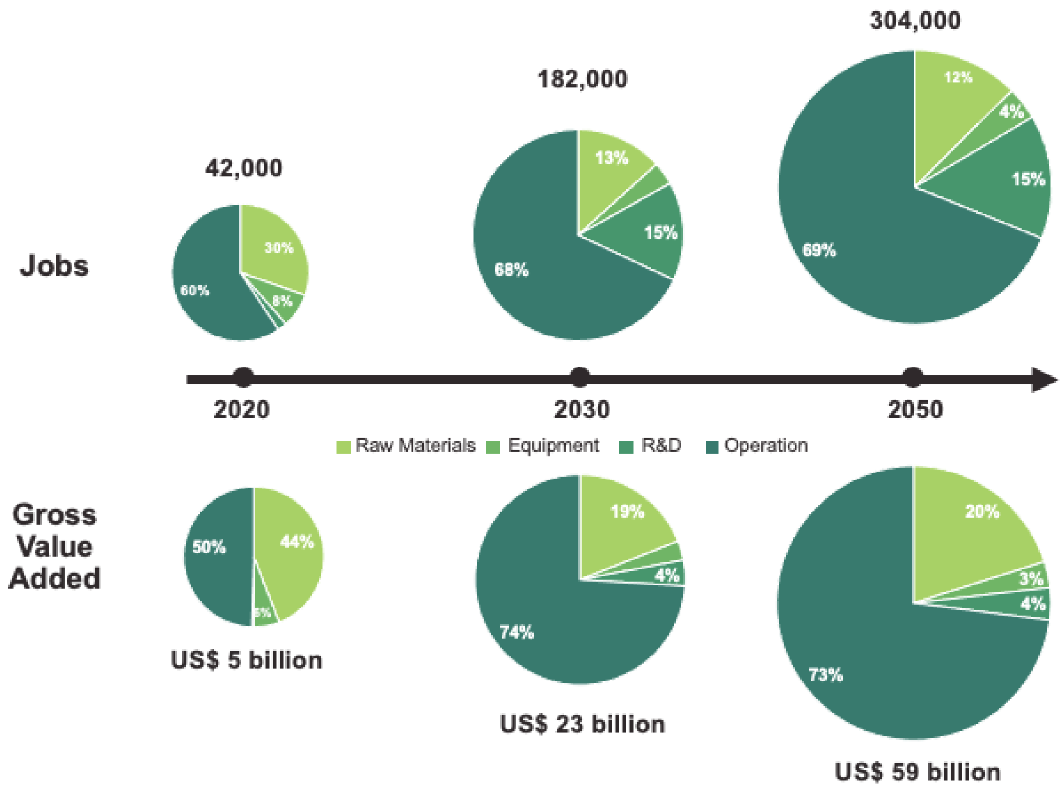
Use of organic pesticides and fertilizers can play an important role in a circular economy. Recycling and reuse of raw materials and products are the main principles of a circular economy. Development of innovative organic fertilizers and pesticides involves reusing organic waste or recycling nutrients from organic waste and thus supports a move toward a circular economy. This move will not only reduce the amount of agricultural waste, but also reduce the need to produce synthetic products used in the agricultural sector.

These benefits are explored in the accompanying report, *Co-benefits of Agricultural Innovation*.

Private benefits: Business opportunities

The transition to organic and innovative synthetic fertilizers and pesticides could deliver more than US$59 billion in GVA and some 304,000 jobs by 2050. Billions of dollars are invested globally each year to restore soil health and control crop diseases and pests. The GVA from organic and innovative fertilizers and pesticides currently stands at about US$5 billion; under a high-innovation scenario, the market for organic and innovative synthetic products is expected to generate US$59 billion by 2050 (see Figure 3). Due to increased demand for highly skilled workers, 262,000 additional jobs are expected to be created by 2030 and 304,000 jobs by 2050.

Figure 3. Economic benefits of the agricultural inputs market.



Source: Vivid Economics.

4. The case for supporting innovation

When complemented by suitable enabling and integrating policies, public support for innovation can meaningfully contribute to meeting the challenge of climate change. The current market for novel inputs remains small relative to the market for conventional inputs but has significant growth potential. Government support is needed to accelerate development and adoption of novel inputs and to unlock the climate, social, and environmental benefits they offer.

Investment need and public support

To realize the full benefits of organic and synthetic fertilizers, public spending on RD&D and on commercialization will need to increase to US$500 million per year and US$600 million per year respectively. Support for organic farming has increased in the last two decades across developed and developing countries, but with several international programs in place, there is scope for a significant increase. Other public support has been made available to accelerate development and adoption of innovative inputs, including the US Department of Agriculture investment of US$72.4 million to boost development of nano fertilizers in the next few years.

Governments can support commercialization of novel inputs by removing market and social barriers. They can support advisory services, regulatory reform, public research, and fiscal incentives, as summarized in Table 2.

An important area of support for the adoption of novel inputs is further public support for knowledge diffusion through subsidized research and extension. Research to develop the evidence base for the environmental and private economic benefits of organic and innovative synthetic products will raise farmers' awareness of these products, increasing their willingness to shift away from traditional synthetic products. In addition, through knowledge diffusion, governments will enhance consumer preferences for organic food and for food produced using innovative synthetic fertilizers and pesticides, which in turn can deliver a price premium, enhancing the business case for the new products.

Advisory and extension services would help dismantle the knowledge and cultural barriers to adoption of novel inputs. Any farming practice shift requires time and effort from the farmer, a cost that can be eased by well-designed advisory services. Because the market for existing inputs is limited to a handful of multinationals, the advisory system tends to be aligned with those inputs' use. Public support for advisory services would help ensure that these services are also realigned with use of organic inputs and other novel inputs.

Further evidence regarding risks and benefits would support development of regulation that is fit for purpose and that would help integrate novel technologies into farming practices. Current regulation is often thought to be overly stringent, presenting a barrier to market entry. An evidence-based case for novel technologies could enable regulation of their use to be made fit for purpose.

Public policy innovation can help re-balance the cost competitiveness of new input technologies relative to conventional inputs. Existing subsidy and taxation systems often fail to reflect the external costs and benefits of input impacts. They fail to cost pollution or provide a revenue stream for public goods, such as carbon sequestration and storage. Reflecting the cost of emission damages from inputs and supporting payments for carbon sequestration in soils, for example, would help increase the cost competitiveness of novel inputs.

Table 2. Barriers that governments can help overcome with appropriate public support

Barrier type	Description	Level of priority	Government support needed
Regulatory	Jurisdictional restrictions	H	Governments can support evidence-based research on the benefits of innovative technologies, thereby mitigating concerns about their potential risks. Then, laws can be adapted to enable a safe environment for these solutions to be commercialized and integrated into responsible farming practices.
Economic	High upfront cost for innovative synthetic products	H	Governments can: ○ Directly invest in R&D, which will lower technology costs through learning by doing. ○ Increase the prices of traditional synthetic products using public economic instruments, such as taxes, or stringent climate change policies and regulations, such as carbon prices. ○ Lower prices using public economic instruments such as subsidies.
	High production costs for organic products	L	Governments can reduce the relatively high production cost of organic farming by lowering organic food prices using public economic instruments such as subsidies.
Informational	Knowledge gaps	H	Governments can enhance farmers' acceptance of organic and innovative synthetic fertilizers and pesticides by providing information about their economic and environmental benefits. Similarly, they can increase consumer preferences for food products being produced in a sustainable way by providing information about the products' environmental impact. Advisory support can help farmers bear the time and effort costs required to change farming practices and adopt novel inputs.

Source: Vivid Economics.
Note: H = high, M = medium, L = low relative priority

References

Case, S. D. C. et al. 2017. "Farmer perceptions and use of organic waste products as fertilizers: A survey study of potential benefits and barriers." *Agricultural Systems* 151:84–95. https://doi.org/10.1016/j.agsy.2016.11.012.

d'Amour, Christopher Bren, et al. 2016. "Future urban land expansion and implication for global croplands." *Proceedings of the National Academy of Sciences* 114 (34): 8939-8944. DOI: 10.1073/pnas.1606036114.

Diaz, Robert J., and Rutger Rosenberg. 2008. "Spreading dead zones and consequences for marine ecosystems." *Science* 321(5891):926–929. DOI: 10.1126/science.1156401.

Erisman, Jan Willem, et al. 2008. "How a century of ammonia synthesis changed the world." *Nature Geoscience* 1:636–639. https://www.nature.com/articles/ngeo325.

Halvorson, Ardell D., et al. 2014. "Enhanced-efficiency nitrogen fertilizers: Potential role in nitrous oxide emission mitigation. *Agronomy* 106(2). https://doi.org/10.2134/agronj2013.0081.

IEA (International Energy Agency). 2021. *Ammonia technology roadmap*. https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf.

IPCC (Intergovernmental Panel on Climate Change). 2014. *Climate change 2014: Mitigation of climate change*. www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_full.pdf.

Herrero, Mario, et al. 2020. "Innovation can accelerate the transition towards a sustainable food system." *Nature Food* 1:266-272 DOI: 10.1038/s43016-020-0074-1.

Iqbal, Muhammad Aamir. 2019. "Nano-fertilizers for sustainable crop production under changing climate: A global perspective." DOI: 10.5772/intechopen.89089.

Jensen, Lars Stoumann, et al. nd. *End-user requirements for recycled and bio-based fertilizer products*. https://ec.europa.eu/eip/agriculture/sites/default/files/fg19_minipaper_6_end_user_requirements_en.pdf.

Muller, Adrian, et al. 2017. "Strategies for feeding the world more sustainably with organic agriculture." *Nature Communications* 8(1290). https://doi.org/10.1038/s41467-017-01410-w.

Sustainable Food Laboratory. 2014. *Barriers and opportunities: The challenge of organic gran production in Northeast, Midwest and Northern Great plains*. https://sustainablefoo.wpengine.com/wp-content/uploads/2016/03/Organic-Grain-Report_Final_9.28.14_Short.pdf.

Valin, Hugo, et al. 2014. "The future of food demand: Understanding differences in global economic models." *Agricultural Economics* 45(1):56–67. https://doi.org/10.1111/agec.12089.