THE €3 TRILLION COST OF SAYING NO:
HOW THE EU RISKS FALLING BEHIND IN THE BIOECONOMY REVOLUTION

A new report by the Breakthrough Institute
and the Alliance for Science

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NGT
GMO

Content

Executive summary

The bioeconomy revolution is taking off around the world, driven by new genomic techniques (NGTs) which enable the precise gene editing of plants, animals and micro-organisms. This is delivering better crops, pharmaceuticals, plant-based proteins and much more, and yielding substantial added value to the global economy.

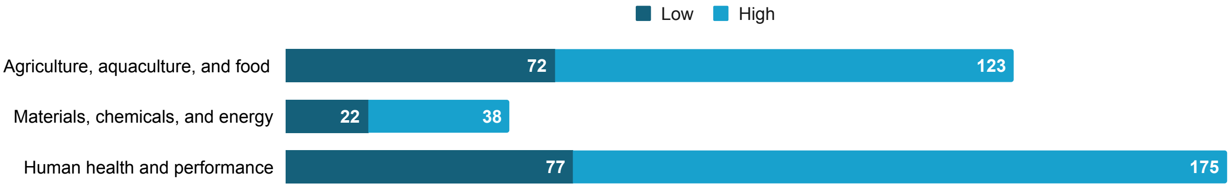
The EU is already getting left behind. Legacy anti-GMO regulations dating back to 2001 are currently applied to gene edited crops, forcing genetics startups to move abroad and leaving the worldwide bioeconomy revolution moribund in Europe. In order to address this, the European Commission made proposals in July 2023 to update the regulation of NGTs more in keeping with scientific progress.

While we view these proposals as insufficiently ambitious, we also acknowledge that they do move in the right direction. However, many NGOs, political parties and member states oppose them outright, seeking to prevent any widespread use of NGTs in Europe. If they succeed in blocking progress on NGTs, Europe will have no bioeconomy revolution.

This report quantifies the cost of saying 'no' to science in Europe over the next decade. In our new analysis:

- We examine the growth potential that could be delivered by NGTs in the agriculture and food; materials, chemicals and energy; and human health sectors.
- We provide low and high estimates for the potential economic benefits of NGT use per year from 2020 up to 2040 in 2020 billions of euros in order to calculate opportunity cost of non-adoption.
- We find that the economic benefits foregone to the EU of not adopting NGTs range from €171-335 billion annually.
- We estimate that this compounds to an economic loss, at the high end estimate, of over €3 trillion of economic benefits over a decade.
- We conclude that the Commission's proposals must progress and indeed be improved upon if Europe is not to give a €3 trillion 'no' to the bioscience revolution.

NGT use in the EU could generate up to €171–335 billion in yearly benefits to humans and the environment between 2020 and 2040.



Category of NGT applications	Range of global yearly potential benefits ($ billions)		Range of global yearly potential benefits (€ billions)		Range of EU yearly potential benefits (€ billions)		Range of EU decadal potential benefits (€ billions)	
	Bottom of range	Top of range	Bottom of range	Top of range	Bottom of range	Top of range	Bottom of range	Top of range
Agriculture, aquaculture, and food	**500**	**850**	**438**	**744**	**72**	**123**	**722**	**1228**
Alternative proteins and synthetic molecules	40	120	35	105	6	17	58	173
Genetic engineering	130	350	114	306	19	51	188	506
Microbiome	330	380	289	333	48	55	477	549
Materials, chemicals, and energy	**155**	**260**	**136**	**228**	**22**	**38**	**224**	**376**
Improve existing fermentation	10	10	9	9	1	1	14	14
New bioroutes	70	110	61	96	10	16	101	159
Novel materials	60	110	53	96	9	16	87	159
Energy production and storage	15	30	13	26	2	4	22	43
Human health and performance	**530**	**1210**	**464**	**1059**	**77**	**175**	**766**	**1748**
Optimize health and traits in future generations	25	50	22	44	4	7	36	72
Prevent, diagnose, and treat diseases	500	1150	438	1007	72	166	722	1661
Gene drives	5	10	4	9	1	1	7	14
			TOTAL		**171**	**335**	**1712**	**3351**

Subcategory rows in white may not add up exactly to category and total rows in blue due to rounding. Figures in column labeled "Range of global yearly potential benefits ($ billions)" are from McKinsey (2020), specifically Exhibit 20, page 111 for "Agriculture, aquaculture, and food"; Exhibit 24, page 129 for "Materials, chemicals, and energy"; Exhibit 17, page 97 for "Optimize health and traits in future generations" and "Prevent, diagnose, and treat diseases"; and page 98 for "Gene drives".

Our study concludes with a stark warning: if the EU continues to exclude new advances in genetics technologies from its economy, then benefits from the bioeconomy revolution - both economic and environmental - will go elsewhere. Europe cannot afford to say no to science.

Introduction

Recent years have seen a revolution in genetics with the advent of what the EU calls 'new genomic techniques' (NGTs) — in short, techniques for making precise changes to the DNA of an organism. The most famous of these is CRISPR, which at its simplest acts as molecular scissors to cut DNA at specifically determined locations — a breakthrough for which its co-inventors, Jennifer Doudna and Emmanuelle Charpentier, shared a Nobel Prize in 2020.

Nobel or not, currently CRISPR is de facto banned in the European Union when it involves the genome editing of plants and animals. This perverse situation is the result of a ruling made by the European Court of Justice (ECJ) in 2018, in response to petitions by anti-GMO groups, that all gene-edited organisms must be considered GMOs and regulated accordingly.[1]

The European Court of Justice decision means that organisms modified using NGTs fall under the antiquated provisions of the EU's 2001 GMO legislation, which was drawn up long before precise gene editing methods like CRISPR were even invented. The 2001 GMO legislation has served as a de facto ban, with no new genetically modified crops approved for cultivation since 2001.[2] In essence, therefore, the ECJ 2018 ruling blocked the deployment of NGTs in Europe. This is indeed precisely why vociferous anti-GMO groups, which oppose scientific innovation in certain arbitrary areas of genetics, support it.

However, by foregoing the use of genetically modified organisms in agriculture, the EU has already missed an opportunity to make agriculture more sustainable by increasing productivity, and therefore decreasing land use, deforestation, and associated greenhouse gas emissions.[3] For gene editing, applications of NGTs are beginning to be used in agriculture elsewhere, and also in the alternative proteins revolution, which could vastly reduce the use of livestock in the human food supply.[4]

This situation has greatly concerned the scientific community, which finds itself locked out of a revolution which is transforming the bioeconomy elsewhere in the world[5]. It has also worried farmers and progressive environmentalists who want to see science deployed in ways that can reduce the impacts of agriculture. Some of the latter recently organised under the banner of 'Give Genes A Chance' to make their case at the Commission and European Parliaments.[6]

Both the 2018 ECJ judgement and the original 2001 GMO legislation are internally inconsistent in that they specifically exclude organisms genetically altered via chemical or radiation mutagenesis, on the basis that these techniques have been in use for a long time and can thus be presumed safe. However, because they cause random genetic mutations, chemical and radiation mutagenesis have the potential to induce many more unintended consequences than the sequence-specific, targeted mutations created by NGTs. The result is a scientifically perverse situation where precise genetic mutations are banned and imprecise ones are permitted.

Moreover, NGTs induce mutations which might occur naturally, given enough time. Unlike transgenic techniques, which shuttle DNA sequences between unrelated species, the types of small mutations that CRISPR can create may

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[1] https://curia.europa.eu/juris/document/document.jsf;jsessionid=53A7A3EC19BBB52D184E3BF91B928A9D?text=&docid=204387&pageIndex=0&doclang=EN&mode=lst&dir=&occ=first&part=1&cid=11104850

[2] Some Bt corn is grown in Europe, primarily in Spain, which received permission before the 2001 GMO legislation was passed.

[3] Kovak, Emma, Dan Blaustein-Rejto, and Matin Qaim. 2022. "Genetically Modified Crops Support Climate Change Mitigation." *Trends in Plant Science* 27 (7): 627–29.

[4] Morach, Benjamin, Björn Witte, Decker Walker, Elfrun von Koeller, Friederike Grosse-Holz, Jürgen Rogg, Michael Brigl, et al. "Food for Thought: The Protein Transformation." BCG Global, 28 March 2023. https://www.bcg.com/publications/2021/the-benefits-of-plant-based-meats.

[5] https://www.mpg.de/13761643/scientists-call-for-modernization-of-the-european-genetic-engineering-law

[6] https://givegenesachance.eu/

also happen in nature or through conventional breeding in exactly the same places and with exactly the same results — scientifically there is no way to tell the difference. Thus, under the EU GMO definition, an identical genetic alteration might be banned or permitted simply on the basis of whether it occurred through 'conventional' breeding or was induced directly by scientists at the molecular level. This is the naturalistic fallacy taken to an extreme.

Even the European Commission has been forced to recognise the absurdity of this situation, and the harm it could potentially cause to food and the environment in Europe. As it notes ruefully in a recent working paper, "there is considerable interest in research on new genomic techniques in the EU, but most of development is taking place outside the EU. Following the ruling of the Court of Justice of the European Union, there have been reports of negative impacts on public and private research on new genomic techniques in the EU due to the current regulatory framework."[7]

As the bioindustry body Europabio wrote in a letter to EU commissioners in November 2022, "European agriculture and some other of the EU's most innovative sectors are at risk of being deprived of scientific progress, putting them at a competitive disadvantage compared to their counterparts. Consequently, Europe's leading position in innovative breeding is at stake, as are EU sustainability goals, jobs in agriculture, bioindustries and their associated value chains, and international trade flows. This does not only concern plant production but is also valid for the livestock sector and the fermentation industry."[8]

The block on innovation by the current regulatory situation regarding NGTs is further evidenced by surveys of companies involved in the sector, both large and small. Over a third of companies

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[7] https://food.ec.europa.eu/system/files/2021-04/gmo_mod-bio_ngt_exec-sum_en.pdf

[8] https://www.europabio.org/policy-proposal-for-new-genomic-techniques-joint-letter-to-the-eu-vice-president-frans-timmermans-and-the-eu-commissioner-stella-kyriakides/


reported that they stopped or reduced their NGT-related R&D activities following the 2018 ECJ ruling, while the largest companies moved their product innovation to more open markets outside the EU[9]. The majority of the companies said they would invest again in NGTs if the GMO regulation was dropped, however.

The European Commission has now received opinions from the European Food Safety Agency (EFSA) and scientific advisory groups which state that NGTs do not introduce any new safety risks and should not be considered GMOs. EFSA's report also points out the numerous potential benefits of NGTs, from climate-resilient crops to pest-resistant plants (requiring less or no pesticide) to vegetables with improved nutrient content. [10]

As EFSA made clear, NGTs introduce "no new hazards compared to both conventional breeding and established genomic techniques". Moreover, off-target mutations potentially induced by CRISPR gene editing "are of the same type as, and fewer than, those mutations in conventional breeding". And critically, "the current risk assessment procedures are rigid and difficult to adapt to scientific progress". This is a damning indictment of the current EU situation, albeit couched in academic language.

As EU-SAGE, a network representing plant scientists at 134 European plant science institutes and societies that have joined forces to provide information about genome editing, stated in a May 2022 press release: "R&D in Europe is lagging behind, mainly due to the current EU legislation, which determines that all genome-edited crop varieties are subject to strict GMO regulations. This EU GMO legislation makes it almost impossible to place such new crop varieties on the market for cultivation in the EU and acts as an

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[9] Jorasch, P. (2020). Potential, Challenges, and Threats for the Application of New Breeding Techniques by the Private Plant Breeding Sector in the EU. *Frontiers in Plant Science*, *11*. https://doi.org/10.3389/fpls.2020.582011

[10] https://www.efsa.europa.eu/sites/default/files/2021-06/10-ec-study-status-new-genomic-techniques.pdf

insurmountable threshold for small and medium plant breeding companies to enter this market."[11] A recent effort to quantify costs of the current regulatory system found that it would likely cost between 6 million and 20 million euros to gain regulatory approval for each new plant developed using NGTs, showing how smaller companies and breeders would be locked out of the market[12].

As the geneticist Devang Mehta wrote in an editorial in the scientific journal Nature in July 2023, "I found the European rejection of plant biotechnology to be an example of first-world privilege," which "has technologically weakened Europe's agriculture sector and driven science talent to other countries." Having grown up in India and moved to Switzerland to "earn a PhD in one of Europe's few remaining plant biotechnology laboratories", he found himself "profoundly disillusioned with the discourse on genetically modified (GM) organisms in Europe, and eventually left to pursue research across the Atlantic."[13]

Notably, the post-Brexit situation in the UK has allowed the passage of a parliamentary bill on gene editing which legalises the use of NGTs in England (Wales and Scotland have separate legislative processes and retain restrictive policies), precisely in recognition of the myriad of potential benefits, an opportunity taken now that the EU's anti-GMO policies have been shed.

More importantly for Europe, the European Commission has itself now produced a proposal for the regulation of NGTs in plants, which — if agreed by the European Parliament and the Council — will take them out of the everlasting regulatory purgatory of GMOs. This proposal, which was released on 5 July 2023, specifically noted that "the application of the current GMO legislation to NGTs is not conducive to the development of innovative products that are potentially beneficial for breeders, farmers, food business operators, consumers and the environment." [14]

The new Commission proposal was summarised succinctly by Mehta writing in Nature. As he explained: "The EU's proposal would create two categories of plants made using NGTs. Category 1 plants would be those with genomic modifications that closely resemble or cannot be easily distinguished from those of conventionally bred plant varieties — even sequencing their genomes might not reveal whether they had been produced using NGTs or conventional breeding techniques. For example, making plants disease resistant by turning off 'susceptibility genes' that are co-opted by plant pathogens often involves modifying just one to three base pairs of DNA out of the millions in a plant's genome. These plants would be freed from older GM rules and regulated similarly to conventionally bred plants, in line with an emerging global consensus on regulating such NGTs. Category 2 plants would be those with more than 20 modified base pairs — those engineered to be resistant to multiple pathogens, for example — and would be subject to many of the same rules as GM plants."

The Commission's proposal was greeted by howls of outrage from anti-science groups, and there is a danger that the blockers - both in the European Parliament and the Council - may carry the day. This study quantifies the potential economic opportunity costs of rejecting gene editing and other NGTs in the agriculture, food, industry, and health sectors, illustrating the high stakes of the EU's ultimate decision.

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[11] Press release EU-SAGE database 30 May 2022. https://www.eu-sage.eu/sites/default/files/2022-05/Press%20release%20EU-SAGE%20database%2030%20May%202022_1_0.pdf

[12] Technopolis Group, Arcadia International and Wageningen University & Research, for DG SANTE of the European Commission. Study to support the impact assessment of legislation for plants produced by certain new genomic techniques. Final report, June 2023. https://op.europa.eu/en/publication-detail/-/publication/44b784a1-1ae3-11ee-806b-01aa75ed71a1/language-en

[13] Mehta, D. (2023). EU proposal on CRISPR-edited crops is welcome — but not enough. Nature, 18 July 2023. https://www.nature.com/articles/d41586-023-02328-8

[14] European Commission. Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on plants obtained by certain new genomic techniques and their food and feed, and amending Regulation (EU) 2017/625. https://food.ec.europa.eu/system/files/2023-07/gmo_biotech_ngt_proposal.pdf

Economic benefits of new genomic techniques (NGTs)

The economic cost of continuing the regulatory status quo regarding NGTs in the EU will be large, likely in the magnitude of hundreds of billions of euros per year across the whole bioeconomy, cumulatively totalling many trillions of lost value over coming decades. While comparatively few plants and food animals altered using NGTs are currently on the market (Table 1) and thus the immediate short-term impact of limiting NGTs may be small, many products are currently being developed with NGTs around the world. As more are commercialised around the world, the economic opportunity cost of the EU restricting NGTs will grow with increasing speed.

The European Commission's new proposal for regulation of NGTs, released on 5 July 2023, dealt specifically with agricultural plants, and did not yet propose a new approach to regulating animals or microorganisms altered using NGTs. It justified this proposal on the basis that: "Safety data are mainly available for plants obtained by targeted mutagenesis and cisgenesis, whereas it is at this stage difficult to draw relevant conclusions on other NGTs and applications in animals and micro-organisms."[15] It defined NGTs as targeted mutagenesis (such as utilising Crispr) and cisgenesis, but not transgenesis, producing plants which in some cases cannot be differentiated genetically from those produced by conventional breeding.

The EU-SAGE database lists (as at July 2023) 744 different genome-edited crop plants, as identified in the worldwide scientific literature.[16] The vast majority of these (672) utilise Crispr technology. Of these, 111 were being developed in EU countries (including overlaps, both in Europe and elsewhere as some products are developed by teams based in more than one country), as compared to 414 in China, 159 in the United States, 37 in Japan, and 33 in South Korea. These numbers illustrate that it is very likely that the EU is already losing business opportunities in this rapidly-growing new sector.

In this report we estimate the potential long-term benefits of NGTs in the EU — and thereby foregone benefits from restricting their use — by examining the potential growth of the bioeconomy and its dependence on NGTs. The EU defines the 'bioeconomy' as follows:

"The bioeconomy covers all sectors and systems that rely on biological resources (animals, plants, micro-organisms and derived biomass, including organic waste), their functions and principles. It includes and interlinks: land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries and aquaculture); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy and services."

It additionally notes that:

"While biotechnology is at the heart of bio-based processes, health biotechnology and biological medicines are not included in the bioeconomy definition".[17]

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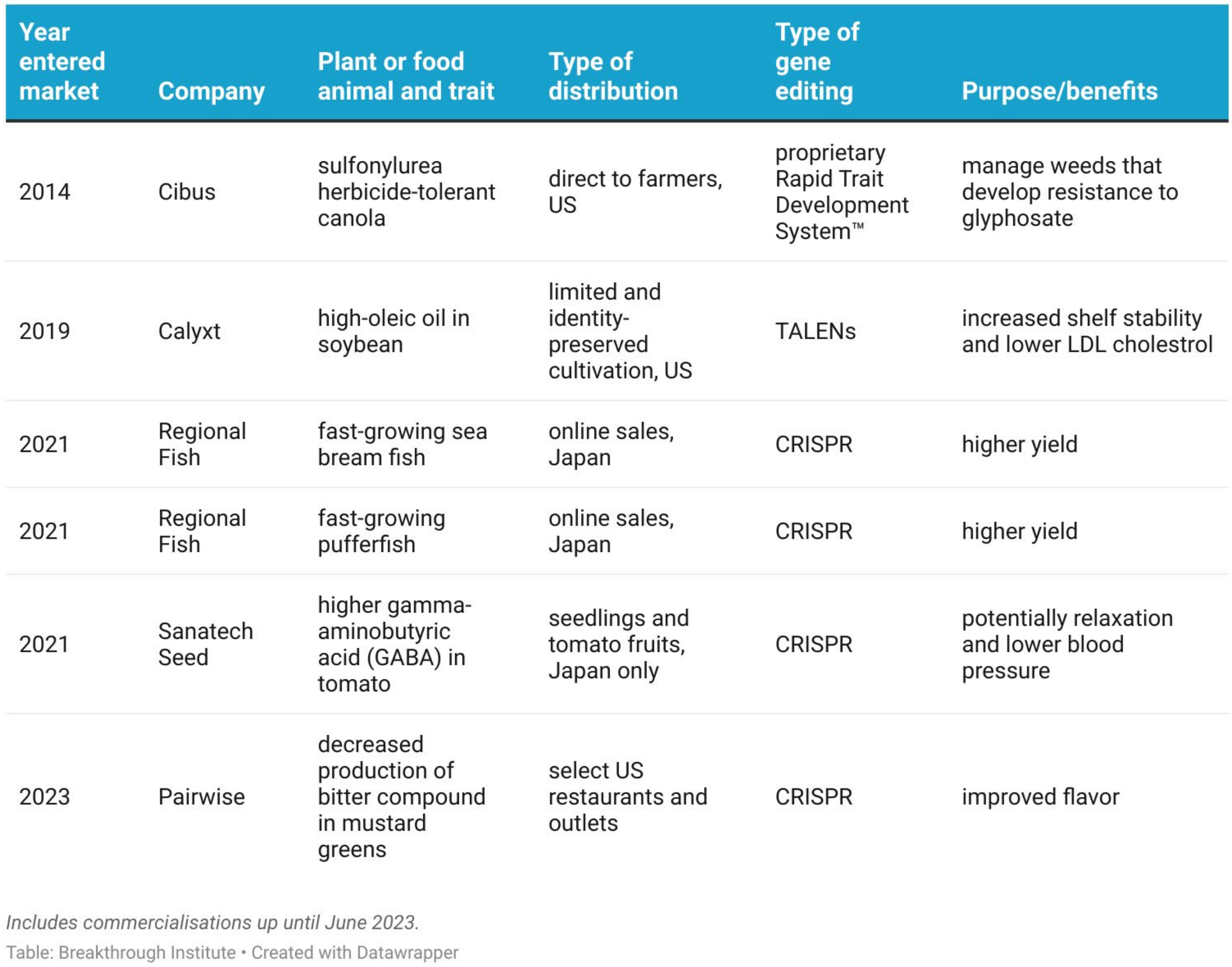
[15] European Commission. Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on plants obtained by certain new genomic techniques and their food and feed, and amending Regulation (EU) 2017/625. https://food.ec.europa.eu/system/files/2023-07/gmo_biotech_ngt_proposal.pdf

[16] https://www.eu-sage.eu/index.php/genome-search

[17] European Commission, Directorate-General for Rese arch and Innovation. 2018. *A sustainable bioeconomy for Europe – Strengthening the connection between economy, society and the environment: updated bioeconomy strategy*. Publications Office. https://data.europa.eu/doi/10.2777/792130.

Table 1: Gene-edited plants and food animals that have been commercialised.



Year entered market	Company	Plant or food animal and trait	Type of distribution	Type of gene editing	Purpose/benefits
2014	Cibus	sulfonylurea herbicide-tolerant canola	direct to farmers, US	proprietary Rapid Trait Development System™	manage weeds that develop resistance to glyphosate
2019	Calyxt	high-oleic oil in soybean	limited and identity-preserved cultivation, US	TALENs	increased shelf stability and lower LDL cholestrol
2021	Regional Fish	fast-growing sea bream fish	online sales, Japan	CRISPR	higher yield
2021	Regional Fish	fast-growing pufferfish	online sales, Japan	CRISPR	higher yield
2021	Sanatech Seed	higher gamma-aminobutyric acid (GABA) in tomato	seedlings and tomato fruits, Japan only	CRISPR	potentially relaxation and lower blood pressure
2023	Pairwise	decreased production of bitter compound in mustard greens	select US restaurants and outlets	CRISPR	improved flavor

Includes commercialisations up until June 2023.

Table: Breakthrough Institute • Created with Datawrapper

The EU bioeconomy is already providing significant value. In 2015, the EU-28 bioeconomy created €620 million of value added and employed 18 million people — these are equal to about 4% of GDP and 8% of total EU-28 employment, respectively[18], making it already more than twice the size of agriculture in economic terms. An industry group estimated in 2016 that bio-based industries would generate an additional 1 million jobs by 2030[19].

The bioeconomy is projected to dramatically grow globally in the coming decades. A report co-written by the World Business Council for Sustainable Development and Boston Consulting Group estimated the total market size of the global bioeconomy as $5.8 trillion in 2018, and a projected $7.7 trillion in 2030.[20]

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[18] Ronzon, T., & M'Barek, R. (2018). Socioeconomic Indicators to Monitor the EU's Bioeconomy in Transition. *Sustainability*, *10*(6), 1745. https://doi.org/10.3390/su10061745

[19] https://www.europabio.org/jobs-growth-generated-by-industrial-biotechnology-in-europe/

[20] WBCSD, and BCG. 2020. "Circular Bioeconomy: The Business Opportunity Contributing to a Sustainable World." https://www.wbcsd.org/contentwbc/download/10806/159810/1

Methodology

A 2020 study from the McKinsey Institute assembled a library of 400 case studies of new applications of biological sciences that are currently technically feasible and likely commercially viable by 2050.[21] Over the next 10–20 years (2030–2040) they estimate that such applications could have a direct economic impact (a narrower measure of value than market size) of $2–4 trillion globally per year.

The McKinsey report's library of case studies spans four main areas:

- human health and performance (at least **$0.5–1.3 trillion** in potential direct economic impact globally);
- agriculture, aquaculture, and food **($0.8–1.2 trillion);**
- consumer products and services **($200–800 billion);**
- and materials, chemicals, and energy (**$200–300 billion).**

The direct economic impact from bioeconomic innovation in the report includes four main benefits: lower costs of production, improved quality of products and services, health improvements, and reductions in greenhouse gas emissions. This may underestimate the economic impacts however. First, industries and products within the bioeconomy are also expected to have other benefits, such as reducing land use or water pollution, which are not factored into these estimates. Second, the growth of the bioeconomy may have indirect impacts; for example, cost reductions within the bioeconomy could spur growth in industries outside of the bioeconomy.

In the EU, the growth of the bioeconomy — in terms of profit, jobs, and other activity — will likely be substantially diminished by maintaining the current extensive barriers to the use of NGTs. In order to quantify the benefits the EU may forego by maintaining extensive restrictions on the use of NGTs, we determined which of the applications included in this McKinsey Institute report might involve the use of NGTs and estimated the proportion of the resulting global benefits that the EU might capture. Our methods are detailed below, and results are shown in Figure 1 and Table 2.

In order to calculate the totals in Figure 1, we started with numbers reported in this study by the McKinsey Institute.[22] Out of the four highest-level categories in the McKinsey report, we included three: human health and performance (section begins on page 95); agriculture, aquaculture, and food (p109); and materials, chemicals, and energy (p127). We excluded the category of consumer products and services (p119) because it does not provide clear or substantial benefits to human health or the environment, which are our main concerns.

We determined which of the applications in the report might involve the use of NGTs by assessing the sub-categories (the most granular level at which estimates of direct economic impact are provided) within the three highest-level categories, and the examples given for each subcategory (a level at which quantified estimates of benefits are not available). Within the high-level categories, we included all sub-categories that included examples that involve the use of NGTs.

Within the high-level category of human health and performance, we included three out of four subcategories (subcategories and examples are listed in Exhibits 16 and 17 on pages 96 and 97 of McKinsey). We excluded the subcategory "improve drug development and delivery" because the examples consisted of applying omics in drug discovery and clinical trials, and while drug production often involves the use of NGTs, these applications of omics do not. Within the subcategory of "improve public health," we included "gene drives" but excluded "DNA sequencing

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[21] Chui, Michael, Matthias Evers, James Manyika, Alice Zheng, and Travers Nisbet. 2020. "The Bio Revolution: Innovations Transforming Economies, Societies, and Our Lives." *McKinsey Global Institute*. https://www.mckinsey.com/industries/life-sciences/our-insights/the-bio-revolution-innovations-transforming-economies-societies-and-our-lives

[22] Chui, Michael, Matthias Evers, James Manyika, Alice Zheng, and Travers Nisbet. 2020. "The Bio Revolution: Innovations Transforming Economies, Societies, and Our Lives." *McKinsey Global Institute*. https://www.mckinsey.com/industries/life-sciences/our-insights/the-bio-revolution-innovations-transforming-economies-societies-and-our-lives

of pathogens to detect outbreaks" (separate estimates on p98 and 99) because sequencing does not involve the use of NGTs. Within the high-level category of agriculture, aquaculture, and food, we included three of the five subcategories (subcategories and examples are listed in Exhibits 19 and 20 on pages 110 and 111). We excluded "food origin, safety, and authenticity" because the examples consisted of genetic tracing of these characteristics of food, which does not involve NGTs. We excluded "marker-assisted breeding" because this technology uses DNA markers for selection but does not use NGTs to alter DNA. Within the high-level category of materials, chemicals, and energy, we included all subcategories (subcategories and examples are listed in Exhibits 23 and 24 on pages 127 and 129) because they all included examples that involve the use of NGTs.

We summed the values at the low end of the range given for each subcategory we chose to include, as well as the high end of the range. The subcategories we chose to include and their low–high ranges are listed in Table 2.

The McKinsey report gives figures in 2020 USD, and we converted figures in dollars from the report to euros using the average 2020 exchange rate, 0.8755.

Next, we multiplied the total in euros by the EU fraction of global value of industries generally included (either wholly or in part) in standard bioeconomy definitions. Data on industry size for countries worldwide is available for download from Eurostat according to NACE categories. We downloaded this Eurostat data at https://ec.europa.eu/eurostat/data/database by navigating -> economy and finance -> national accounts (ESA 2010) -> national accounts - international data cooperation -> annual national accounts - international data cooperation -> gross value added by A*10 industry. We included the following NACE categories: agriculture, forestry, fishing (A); and industry (B–E), which includes mining and quarrying (B); manufacturing (C); electricity, gas, steam and air conditioning supply (D); and water supply, sewerage, waste management and remediation activities (E). Dividing the total of these industries in the EU27 countries in 2016 (the most recent year with complete data available that includes China) by the total of all countries worldwide available in the dataset yielded a fraction of 0.165. The resulting ranges are shown in Figure 1 and Table 2.

The main limitation on our analysis comes from the level of detail provided in estimates of direct economic impact by category of application in the McKinsey report. We summed benefits for categories that include applications of NGTs or applications that could benefit from the use of NGTs (listed in Table 2); however, there was not enough detail to separate applications more precisely by the use of NGTs, so our estimates include whole categories in which some applications involve NGTs and others would likely not. In addition, the McKinsey study cites limitations including that the study used only publicly available data, which means it excludes many new biological applications in the private sector. Finally, new applications may arise after this study was conducted but still be commercialised by 2050, and newer applications are more likely to use NGTs.

Though the McKinsey study includes crop and animal products that are 'genetically engineered', these applications will often also involve the use of NGTs. This is important because the EU's most proximate decision on biotechnology regulations is whether to regulate NGTs differently than GMOs, which could enable the use of crop products of NGTs in EU agriculture, while any change in regulation of GMOs would be further down the line. The term genetically engineered is generally considered synonymous with genetically modified or transgenic, while the term NGT is generally considered synonymous with genome-edited, and is not generally considered to include GMOs.

Applications in the study's category of genetically engineered plants and animals will often also involve the use of NGTs because 1) applications of the most widespread NGT, CRISPR, have been growing quickly, and will make up an increasingly large proportion of biotech crop applications; 2) as time goes on, CRISPR gene editing is increasingly being used to create similar traits to those previously created using genetic engineering/genetic modification/transgenics (e.g. herbicide tolerance), so the proportion of biotech products of NGTs will grow; 3) many countries are choosing to regulate gene-edited crops more like conventionally-bred crops than like GMOs, so it can be cheaper to commercialise a gene-edited crop because the costs of meeting regulatory requirements are lower. Therefore, some of the plants and animals in this category may be developed using gene editing rather than genetic modification.

Table 2: NGT use in the EU could generate up to €171–335 billion in yearly benefits to humans and the environment between 2020 and 2040.

Category of NGT applications	Range of global yearly potential benefits ($ billions)		Range of global yearly potential benefits (€ billions)		Range of EU yearly potential benefits (€ billions)		Range of EU decadal potential benefits (€ billions)	
	Bottom of range	Top of range	Bottom of range	Top of range	Bottom of range	Top of range	Bottom of range	Top of range
Agriculture, aquaculture, and food	**500**	**850**	**438**	**744**	**72**	**123**	**722**	**1228**
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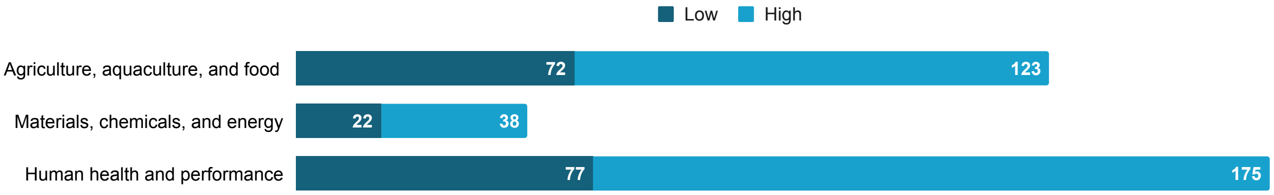
Prevent, diagnose, and treat diseases	500	1150	438	1007	72	166	722	1661
Gene drives	5	10	4	9	1	1	7	14
				TOTAL	**171**	**335**	**1712**	**3351**

Subcategory rows in white may not add up exactly to category and total rows in blue due to rounding. Figures in column labeled "Range of global yearly potential benefits ($ billions)" are from McKinsey (2020), specifically Exhibit 20, page 111 for "Agriculture, aquaculture, and food"; Exhibit 24, page 129 for "Materials, chemicals, and energy"; Exhibit 17, page 97 for "Optimize health and traits in future generations" and "Prevent, diagnose, and treat diseases"; and page 98 for "Gene drives".

Over the next 10–20 years, we estimate that the EU might forgo **€123 billion** of the annual economic benefits of agriculture, aquaculture, and food, in the absence of enabling regulations for NGTs, summing to **€1.2 trillion** over the decade. (Figure 1 and Table 2; subcategories shown in Table 2). For comparison, EU agriculture generated an estimated gross value added of €189 billion in 2021[23].

Figure 1: NGT use in the EU could generate up to €171-335 billion in yearly benefits between 2020 and 2040



Within the category of 'agriculture, aquaculture, and food,' McKinsey estimates that genetic engineering — including crops and food animals — could generate €114–306 billion globally in direct benefits annually, thanks to improvements in productivity, reductions in mortality rates, and the production of higher-quality products with enhanced taste and nutritional value. We estimate that the EU might capture up to €51 billion of this annual total, given enabling regulations (Figure 1 and Table 2; subcategories shown in Table 2). However, given the current de facto ban on crop biotechnology the EU will forgo virtually all of these benefits.

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[23] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Performance_of_the_agricultural_sector

NGT use in the EU could generate up to €171-335 billion in yearly benefits between 2020 and 2040

Other than the category of genetically engineered plants and animals discussed above, the rest of the categories in the McKinsey report use biotechnology — including GMOs and NGTs — for some applications but not others. The categories we chose to include are shown in Table 2. For example, McKinsey estimates that the 'microbiome' category within 'agriculture, aquaculture, and food' — including microbiome diagnostics and probiotics and microbial seed and soil treatments — could create an annual direct impact of €289–333 billion globally in the next 10–20 years. We estimate that the EU might capture up to €55 billion of this total, given enabling regulations (Figure 1 and Table 2; subcategories shown in Table 2). While the €289–333 billion impact of this category would be affected to some extent by reduced access to NGTs in the EU, this is likely less so than for plant and animal production. Though some companies are using gene editing to improve the ability of certain microbes to fertilise plants, many microbial applications in agriculture use naturally occurring, wild type or unmodified microorganisms.

Within the 'agriculture, aquaculture, and food' category, McKinsey reports that 'alternative proteins and synthetic molecules' — including cultured meat and plant-based and synthetic proteins — could create an annual direct economic impact globally of €35–105 billion. We estimate that the EU might capture up to €17 billion of this total, given enabling regulations (Figure 1 and Table 2; subcategories shown in Table 2). While alternative proteins and synthetic molecules are largely produced in an industrial setting — within which many biotechnology applications are unlikely to be threatened by new legislation on NGT use — their use for human food consumption means they have an uncertain future. As of April 2022, the European Commission had not yet approved[24] any precision fermentation-derived food product, and to our knowledge this is still the case.

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[24] Southey, Flora. "Regulating precision fermentation: Challenges and opportunities in marketing microbially-derived foods in Europe." *Food Navigator*, 14 April 2022. https://www.foodnavigator.com/Article/2022/04/14/Regulating-precision-fermentation-Challenges-and-opportunities-in-marketing-microbially-derived-foods-in-Europe#.

“CASE STUDY: IMPOSSIBLE IN THE EU?”

One product currently undergoing the EU’s cumbersome assessment is Impossible Foods’ soy leghemoglobin, which is produced via precision fermentation in genetically modified yeast in an industrial setting. Because Impossible Foods’ final product contains host proteins, it is regulated under EC 1829/2003 legislation on GMOs, meaning that even if the European Food Safety Authority assessment is positive, the decision goes to the European Commission and member states, of which a 55% majority must vote to approve the product. The company submitted its dossier for regulatory approval to place the product on the market in October 2019, and the dossier was not validated until late December 2021, after which the process was immediately paused to request more information, and remains on hold at the time of writing (July 2023), with the pause expected to last until the end of 2023.[25] Approval is an unlikely prospect, and refusal to approve this obviously more sustainable plant-based product would have a chilling effect on the entire sector which is impossible to quantify but nevertheless very real. For this reason, our attempts to quantify the benefits foregone might very well be substantial underestimates.

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[25] https://open.efsa.europa.eu/questions/EFSA-Q-2019-00651

The EU has used many industrial products of genetically modified microbes for decades, including the medicine insulin (manufactured using genetically modified *E. coli* microbes since 1982), and cheese made using the enzyme chymosin (manufactured using genetically modified *E. coli* microbes since 1991). These products, insulin and chymosin, are not themselves genetically modified, because they are purified from the microbes used to produce them.

Considering that industrial products of NGTs have been manufactured in the EU for decades, and that these uses are in a contained environment, EU actions on NGTs will likely not directly impact these uses. However, if EU regulatory blockages on NGTs did negatively affect the use of industrial biotechnology, the impacts would be massive: McKinsey estimates €136–228 billion in direct economic impact by 2040 for ‘materials, chemicals, and energy’, including products like food and feed ingredients, biopesticides/biofertilizers, industrial enzymes, and biofuels. We estimate that the EU might capture up to €38 billion of this total, given enabling regulations (Figure 1 and Table 2; subcategories shown in Table 2).

Even if changes in EU gene editing regulations do not directly limit the use of NGTs in industrial settings, maintaining restrictive regulations on gene editing in agricultural plants would impact the use of plant-derived feedstocks. Currently in the EU, 10% of the feedstocks used for chemical production are bio-based, which is expected to increase to 25% by 2030. The main feedstocks are sugar, starch, vegetable oil, bioethanol, natural rubber, and glycerol.[26] These feedstocks are mainly derived from wheat; corn, sorghum and other coarse grains; sugar beets; and oilseeds (over half of EU oilseed crop is rapeseed). Genetically modified varieties of some of these crops, such as corn and sugar beet, have been developed with greater

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[26] Popp, József, Sándor Kovács, Judit Oláh, Zoltán Divéki, and Ervin Balázs. 2021. “Bioeconomy: Biomass and Biomass-Based Energy Supply and Demand.” *New Biotechnology* 60: 76–84. https://doi.org/10.1016/j.nbt.2020.10.004.

yields and are grown widely in many non-EU countries.[27] Besides increasing yields, genetic improvement can also increase the sugar content of biomass feedstock crops, or otherwise alter their makeup to increase efficiency of digestion or conversion into bioeconomy products. NGTs are the future of crop genetic improvement, and foregoing their use in agriculture would mean losing out on improved efficiency and decreased environmental impacts in bio-based industrial production.

Finally, McKinsey estimates €464–1059 billion yearly in direct economic impact from the category of 'human health and performance,' including optimise health and traits in future generations; prevent, diagnose, and treat diseases; and gene drives. We estimate that the EU might capture up to €175 billion of this total, given enabling regulations (Figure 1 and Table 2; subcategories shown in Table 2).

Out of the total of up to €171–335 billion in annual benefits, different categories of applications have different degrees of benefits (Figure 1) and face varying degrees of risk based on EU regulatory decisions on NGTs. Based on the most proximate regulatory decision the EU must make on NGTs, only NGTs in agricultural plants would be directly impacted. However, if the EU does not begin to allow the use of NGTs in crop plants, it will likely not choose to allow NGT use in livestock, microbes for agricultural uses, or gene drives in the environment, thereby foregoing up to €107 billion in annual benefits (total of 'agriculture, aquaculture, and food' in Table 2, minus 'alternative proteins and synthetic molecules,' plus 'gene drives' from 'human health and performance'). Further, if the EU does not start approving contained uses of NGTs to make food products, it risks foregoing up to €17 billion for alternative proteins alone (subcategory of 'alternative proteins and synthetic molecules' within 'agriculture, aquaculture, and food' in Table 2). If the EU does not allow NGT use for 'human health and performance,' it risks foregoing up to a further €175 billion (Figure 1 and Table 2). Finally, if anti-NGT sentiment expands further and the use of NGTs for industrial production is reduced, the EU risks foregoing up to an additional €38 billion in yearly benefits (category of 'materials, chemicals, and energy' in Figure 1 and Table 2).

Restrictive EU regulations on NGTs could put the bloc at a competitive disadvantage internationally. The UK, for example, recently adopted regulations for NGTs that allow much more use of the technology than current EU regulations. This could give the UK a significant edge in the development and commercialisation of new bio-based products and technologies. The UK has also committed to support research and innovation using genetic engineering and CRISPR in fields such as manufacturing and engineering biology.[28] The UK's innovation strategy includes increasing public R&D investment to £22 billion per year, and increasing visa routes for skilled workers, building upon the UK's existing position as the third largest bioeconomy cluster in the world.

In addition to competition from the UK, India and China also have bioeconomy strategies and both have stated plans to become dominant bioeconomies.[29] China, along with the US, already conducts several-fold more research than the EU on market-oriented gene-edited plants.[30] Though the EU allows research on gene editing in plants, member states are falling behind in this research field. As the European commission notes, "there is considerable interest in research on new genomic techniques in the EU, but most of development is taking place outside the EU. Following the ruling of the Court of Justice of the European Union, there have been reports of negative impacts on public and private research on new genomic techniques in the EU due to the current regulatory framework."[31]

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[27] Klümper, Wilhelm, and Matin Qaim. 2014. "A Meta-Analysis of the Impacts of Genetically Modified Crops." *PLoS ONE* 9 (11). https://doi.org/10.1371/journal.pone.0111629.

[28] "UK Innovation Strategy: Leading the Future by Creating It." 2021. https://www.gov.uk/government/publications/uk-innovation-strategy-leading-the-future-by-creating-it.

[29] Hodgson, Andrea, and Mary E. Maxon. 2022. "The U.S. Bioeconomy: Charting a Course for a Resilient and Competitive Future." https://doi.org/10.55879/D2HRS7ZWC.

[30] Menz, Jochen, Dominik Modrzejewski, Frank Hartung, Ralf Wilhelm, and Thorben Sprink. 2020. "Genome Edited Crops Touch the Market: A View on the Global Development and Regulatory Environment." *Frontiers in Plant Science* 11: 1–17. https://doi.org/10.3389/fpls.2020.586027.

[31] https://food.ec.europa.eu/system/files/2021-04/gmo_mod-bio_ngt_exec-sum_en.pdf

Supporting evidence: Applications of NGTs and their benefits

Using NGTs in crops, livestock, and microbes could have a wide variety of benefits for farmers and other producers, the environment, and consumers. Below are some examples of gene editing and genetic modification being used to increase crop yields, disease resistance, insect resistance, and drought tolerance; livestock productivity, efficiency, and disease resistance; and microbe fertilisation of crops.

Table 3: Gene-edited products can have a wide range of benefits.

Gene editing application	Example	Reduce production costs	Decrease land use	Lower GHG emissions	Increase nutrition	Improve animal welfare
Increase crop yields	decrease canola pod shatter (Cibus)	x	x	x		
Reduce synthetic fertilizer use	improve nitrogen-fixing microbes (Wen et al, 2021)	x		x		
Increase animal disease resistance	PRRS-resistant pig (Burkard et al, 2018)	x	x	x		x
Increase crop disease resistance	potato resistant to Y-virus (Makhotenko et al, 2019)	x	x	x		
Increase drought tolerance	drought tolerant maize (Shi et al, 2017)	x	x	x		
Improve nutrition/flavor	less bitter mustard greens (Pairwise)				x	
Improve animal welfare	hornless cattle (Mueller et al, 2021)					x
Reduce food waste	non-browning mushroom (Choi et al, 2023)		x	x		

Table: Breakthrough Institute • Created with Datawrapper

Increase crop yields

Increasing crop yields can contribute to producing more food, fuel, and fibre while reducing cropland expansion. Crop yield increases can also increase farmer income by enabling more production and greater profit from a limited amount of land. Crop yield increases have historically played a crucial role in limiting land conversion and associated emissions — without them, land use for cereal production would have expanded over 6 times more than it did over the last 60 years.[32] Improvements in crop genetics have contributed roughly half of historical yield gains,[33] making genetic improvement a powerful way to reduce emissions.[34] In addition, reducing agricultural land use expansion can help protect biodiversity, because agriculture is the greatest driver of deforestation and biodiversity loss.[35],[36],[37]

Using biotechnology to increase crop yields has a large, but largely overlooked, potential to reduce agriculture's climate footprint. One meta-analysis estimated that existing genetically engineered traits for insect resistance and herbicide tolerance have increased yields by 22% across industrialised and developing countries.[38] By some estimates, dramatic improvements in plant breeding, including biotechnology (genetic modification, gene editing, NGTs broadly), could reduce global agricultural greenhouse gas emissions by almost 1 Gt CO_2e/year by 2050, mainly by increasing yields.[39] Though biotechnology is not the only contributor to crop genetic improvement, a greater variety of tools provides flexibility for the challenge of continuing crop yield growth in the face of intensifying climate change. As the speed of climate change increases,[40] faster tools like genetic engineering and genome editing will enable faster adaptation compared to slower tools like conventional breeding.

EU adoption of existing genetically modified crops could increase yields, enabling an increase in exports or decrease in imports, both of which could help avoid deforestation in other countries from which the EU buys millions of tonnes of corn and soy (mainly for livestock feed). For example, increasing EU soybean yields domestically could allow the bloc to decrease soybean imports from 30 million tonnes, much of which comes from Brazil where soybean production is linked to deforestation in the Amazon.[41] Not only could the EU, by producing more soybeans, help preserve the high-biodiversity Brazilian Amazon, it could also decrease future growth in greenhouse gas emissions from associated deforestation. Although raising yields in one place does generally reduce the need to convert new cropland elsewhere — because global crop demand and production is rising — it is nonetheless difficult to predict how land use will respond to crop yield increases in a particular situation because outcomes vary.[4243] In order to mitigate agricultural land use expansion when yields increase, strategies such as land use zoning, land taxes and subsidies, and standards and certifications can be employed.[44]

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[32] https://ourworldindata.org/grapher/cereal-land-spared

[33] https://www.ers.usda.gov/webdocs/publications/42517/13599_aib786d_1_.pdf?v=0

[34] https://research.wri.org/wrr-food

[35] https://ourworldindata.org/environmental-impacts-of-food

[36] https://ourworldindata.org/what-are-drivers-deforestation

[37] https://www.unep.org/news-and-stories/press-release/our-global-food-system-primary-driver-biodiversity-loss

[38] Klümper, Wilhelm, and Matin Qaim. 2014. "A Meta-Analysis of the Impacts of Genetically Modified Crops." *PLoS ONE* 9 (11). https://doi.org/10.1371/journal.pone.0111629.

[39] Searchinger, Tim, Richard Waite, Craig Hanson, and Janet Ranganathan. 2019. "Creating a Sustainable Food Future." www.SustainableFoodFuture.org. [This link redirects to https://research.wri.org/wrr-food.]

[40] https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

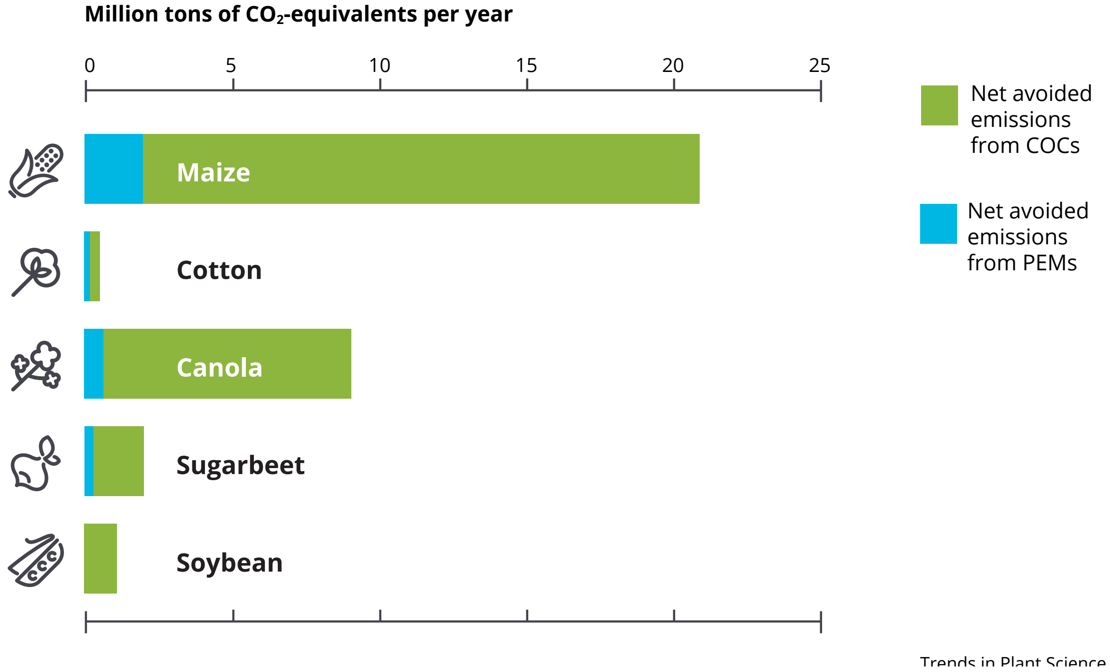
[41] Fuchs, Richard, Calum Brown, and Mark Rounsevell. 2020. "Europe's Green Deal Offshores Environmental Damage to Other Nations." *Nature* 586: 671–73. https://doi.org/10.1038/d41586-020-02991-1.

[42] Rodríguez García, Virginia, Frédéric Gaspart, Thomas Kastner, and Patrick Meyfroidt. 2020. "Agricultural Intensification and Land Use Change: Assessing Country-Level Induced Intensification, Land Sparing and Rebound Effect." *Environmental Research Letters* 15. https://doi.org/10.1088/1748-9326/ab8b14.

[43] https://ourworldindata.org/grapher/land-use-vs-yield-change-in-cereal-production

[44] Phalan, Ben, Rhys E. Green, Lynn V. Dicks, Graziela Dotta, Claire Feniuk, Anthony Lamb, Bernardo B.N. Strassburg, David R. Williams, Erasmus K.H.J. zu Ermgassen, and Andrew Balmford. 2016. "How Can Higher-Yield Farming Help to Spare Nature?" *Science* 351 (6272): 450–51. https://doi.org/10.1126/science.aad0055.

Figure 2. Genetically modified crops in the EU could increase yields and avoid greenhouse gas emissions.



Abbreviations: COCs, carbon opportunity costs of land use; PEMs, production emissions. Graph modified from Kovak, Blaustein-Rejto, and Qaim (2021).[47]

There are no analyses of the potential emissions reductions associated with gene-edited crops that increase yields, but the Breakthrough Institute previously estimated that growing existing genetically modified crops in the EU could reduce global greenhouse gas emissions by 33 million tonnes of CO_2 equivalents per year ($MtCO_2e/yr$), which is equivalent to 7.5% of the EU's 2017 total agricultural greenhouse gas emissions.[45] Figure 2 shows the breakdown of emissions reductions by crop. Another Breakthrough Institute analysis estimated that growing drought-tolerant genetically modified HB4 wheat in Argentina — a country which is increasingly struggling with drought — could reduce global greenhouse gas emissions by 0.86–1.29 $MtCO_2e/yr$, which is equal to 34–51% of the yearly on-farm emissions from Argentina's wheat production.[46]

Although none of the gene-edited crops on the market thus far were created to improve yields, there are gene-edited products in development — some close to market — for which companies have estimated the potential yield increase. For example, Inari is using gene editing to increase corn, wheat, and soybean yields, with a goal of up to 20% yield increase, in addition to reducing the amount of water and nitrogen fertiliser needed to grow corn. Inari's CEO said in 2022 that they are close to reaching the yield target in soybeans.[48] A different approach to increasing crop yields is a trait that decreases crop loss during harvesting, as Cibus is doing with a canola pod shatter trait.

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[45] Kovak, Emma, Dan Blaustein-Rejto, and Matin Qaim. 2022. "Genetically Modified Crops Support Climate Change Mitigation." *Trends in Plant Science* 27 (7): 627–29. https://doi.org/10.1016/j.tplants.2022.01.004.

[46] Kovak, Emma, and Dan Blaustein-Rejto. "The World's First Genetically Engineered Wheat Is Here." The Breakthrough Institute, 4 April 2022. https://thebreakthrough.org/issues/food-agriculture-environment/the-worlds-first-genetically-engineered-wheat-is-here.

[47] Kovak, Emma, Dan Blaustein-Rejto, and Matin Qaim. 2022. "Genetically modified crops support climate change mitigation." *Trends in Plant Science* 27 (7): 627–29.

[48] https://www.ft.com/content/337ba132-cc33-42a9-9df3-cd53114200bc

Increase crop stress tolerance

Genetic improvement could increase crop tolerance of biotic and abiotic stresses, including disease, pests, and drought. Potential benefits include increasing yields, decreasing the cost and environmental impact of inputs (pesticides, herbicides, water, etc), and increasing farmer income. For example, by increasing crop drought tolerance, gene editing could reduce crop loss in seasons with drought conditions, thereby increasing yields, and reduce the cost of increased irrigation to make up for lack of rainfall and the draw on limited groundwater resources.

Existing genetically modified crops with herbicide-tolerant and insect-resistant traits raise farm incomes, by an average $103 per hectare in 2020 for widely grown crops.[49] Farmers in developed countries experience an average $3 increase in income for each additional dollar they spend on genetically modified seeds, above the cost of conventional seeds.[50] Farmer income gains associated with use of herbicide-tolerant, insect-resistant, and drought-tolerant genetically modified seeds may be due to several factors: more cost-effective, less expensive, and easier weed control; lower expenditures on insecticides and pest monitoring; lower spending on irrigation; and yield increases due to improved weed control, reduced pest damage or improved drought tolerance.[51]

Many genetically modified transgenic products can be made more efficiently and precisely using NGTs, and likely will be soon. Partially because of regulatory barriers and public perception, companies are moving to use NGTs rather than genetic modification to make non-transgenic products that will not fall under the same restrictive GMO regulations, and may be viewed more favourably by the public. For example, the agrochemical company BASF is working with Kaiima, a small start-up, to make non-GMO herbicide-tolerant crops using gene editing.

Support small businesses

Regulating NGTs less restrictively than GMOs can support small and medium-sized businesses in multiple ways. First, it is easier and cheaper to develop improved crops with NGTs than with GM technology, which makes the technology more accessible to smaller developers of gene-edited products. In 2015, Argentina became the first country to determine that many products of gene editing would not fall under existing GMO regulations. A subsequent four-year study showed that compared to first-generation GMOs, gene-edited products moved faster to commercialisation, were led by smaller developers, and covered more diverse traits and organisms; the number of regulatory decisions is

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[49] Brookes, Graham. 2022. "Farm Income and Production Impacts from the Use of Genetically Modified (GM) Crop Technology 1996-2020." *GM Crops and Food* 13 (1): 171–95. https://doi.org/10.1080/21645698.2022.2105626.

[50] Brookes, Graham. 2022. "Farm Income and Production Impacts from the Use of Genetically Modified (GM) Crop Technology 1996-2020." *GM Crops and Food* 13 (1): 171–95. https://doi.org/10.1080/21645698.2022.2105626.

[51] Brookes, Graham. 2022. "Farm Income and Production Impacts from the Use of Genetically Modified (GM) Crop Technology 1996-2020." *GM Crops and Food* 13 (1): 171–95. https://doi.org/10.1080/21645698.2022.2105626.

shown in Figure 3.[52] Second, an increase in beneficial gene-edited traits available in fruit and vegetable crops may provide more benefit to smaller farms that have tighter margins and are less likely to profit from commodity crops. For example, determinations of non-GMO status by Argentina's regulatory authorities comprised a larger proportion of fruit and vegetable crops and a smaller proportion of commodity crops than the 23-year period of GMO crop approvals.[53]

Regulating NGTs less restrictively than GMOs can encourage competition and help create a less concentrated market; in contrast, more extensive regulatory requirements increase the cost of bringing a product to market and can thereby deter small companies and start-ups. These high costs can decrease competition and support market concentration by large multinational companies. Indeed, the agricultural seed industry has seen dramatic consolidation over the past three decades, leading to the 'big six' companies, which with mergers and acquisitions completed in 2017 and 2018 became the 'big four' (Bayer-Monsanto, DowDuPont/Corteva, ChemChina-Syngenta, and BASF).[55]

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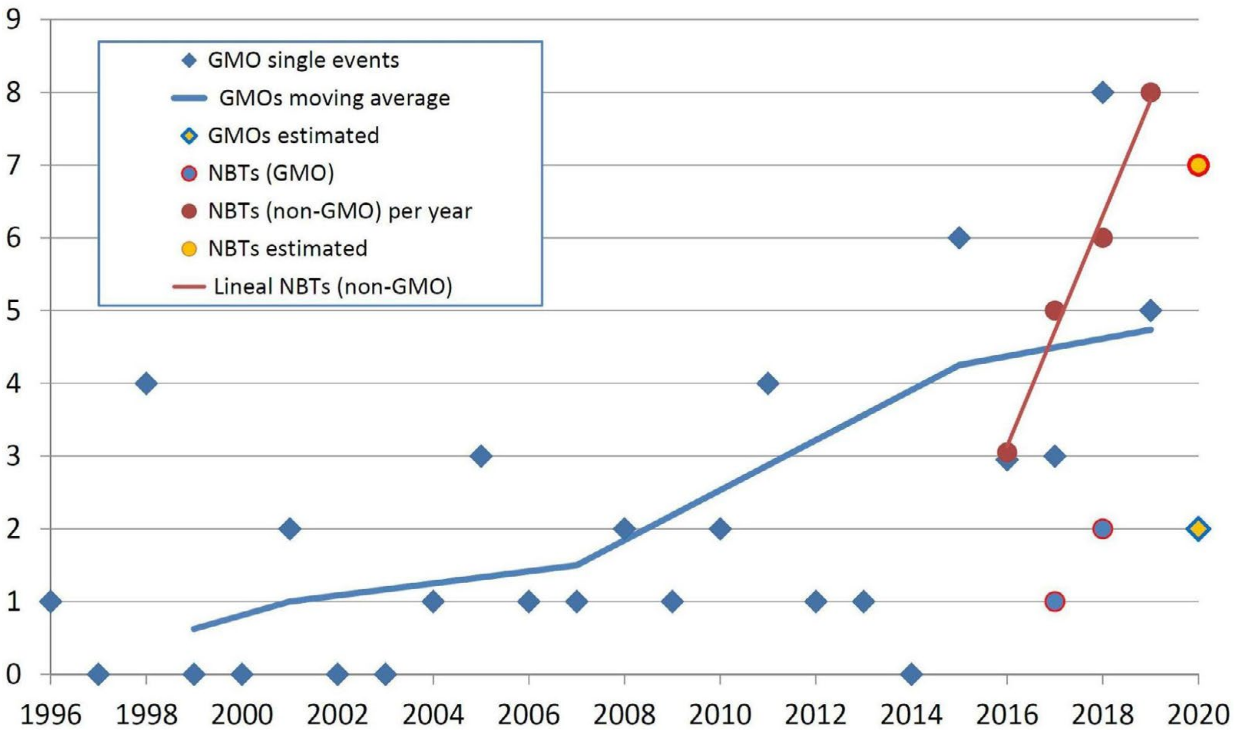
[52] Whelan, A.I., P. Gutti, and M.A. Lema. 2020. "Gene Editing Regulation and Innovation Economics." *Frontiers in Bioengineering and Biotechnology* 8:303. https://doi.org/10.3389/fbioe.2020.00303.

[53] Whelan, A.I., P. Gutti, and M.A. Lema. 2020. "Gene Editing Regulation and Innovation Economics." *Frontiers in Bioengineering and Biotechnology* 8:303. https://doi.org/10.3389/fbioe.2020.00303.

[54] Whelan, A.I., P. Gutti, and M.A. Lema. 2020. "Gene Editing Regulation and Innovation Economics." *Frontiers in Bioengineering and Biotechnology* 8:303. https://doi.org/10.3389/fbioe.2020.00303.

[55] https://www.seedworld.com/from-big-six-to-big-four/

Figure 3. Argentina is making more regulatory decisions on products of New Breeding Techniques (NBTs) than for GMOs



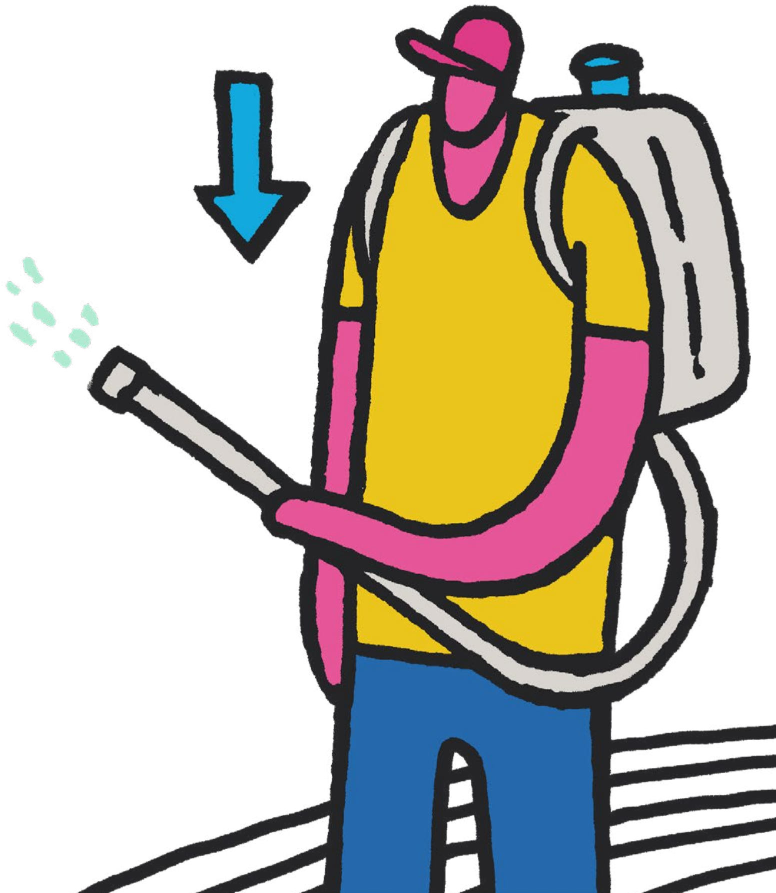
NBTs is another term for NGTs. Figure included from Whelan et al. (2020).[54] Original figure legend: "The timeline of GMO approvals in Argentina and the determination of conventional or GMO status for products obtained using different NBTs. The horizontal axis represents the year of the regulatory decision, and the vertical axis represents the number of products."

Reduce synthetic fertiliser use

NGTs can be used to alter microbes to provide more crop nutrients, reducing both farmer input costs and the environmental impacts of fertiliser use. Companies like Kula Bio have products made up of naturally occurring microbes that have been treated to increase their ability to capture nitrogen from the air,[56] whereas others like Pivot Bio take a gene editing approach.[57] Both aim to improve microbes' nitrogen fixation activity and use these microbes to replace some applications of synthetic nitrogen fertiliser with a potentially cheaper input.

Pivot Bio has used gene editing to improve a nitrogen-producing microbe that farmers can apply to corn and to small grain crops such as barley, millet, oats, sorghum, sunflower, and spring wheat.[58] The company claims the microbes fix enough nitrogen to replace an average of 36 pounds of nitrogen per acre in corn operations,[59] cutting fertiliser costs and increasing plant biomass. One three-year study found that corn producers that replaced a portion of their synthetic nitrogen with nitrogen from one of Pivot Bio's microbial products saw an additional profit of $16.5 per acre ($40.8 per hectare).[60] If all farmers across the EU's roughly 8.9 million hectares of maize area saw this improvement,[61] total profits would rise by about $363 million (€330 million).

In addition, producing nitrogen with these microbes has about a 98% lower carbon footprint than doing so through the conventional Haber-Bosch process.[62] This and other gene-edited microbial fertiliser products have the potential to dramatically cut the €1.9 billion spent on importing nitrogenous fertiliser into the EU,[63] the 31 million tonnes CO$_2$e produced per year by the European fertiliser industry,[64] and the roughly €500 million that the industry pays for allowances under the Emissions Trading Scheme.[65] If synthetic fertiliser application was reduced by 36 pounds per acre (~41 kg per hectare) in maize production across the EU, it would result in about 133,000 tonnes nitrogen less (or 13% less) synthetic fertiliser application on maize cropland.[66,67]



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[56] https://www.fastcompany.com/90718173/if-farmers-spray-these-microbes-on-crops-they-dont-need-fertilizer

[57] https://www.desmoinesregister.com/story/money/business/2022/10/09/microbe-fertilizer-startups-look-to-expand-iowa-farms/8086016001/

[58] Wen, Amy, Keira L. Havens, Sarah E. Bloch, Neal Shah, Douglas A. Higgins, Austin G. Davis-Richardson, Judee Sharon, et al. 2021. "Enabling biological nitrogen fixation for cereal crops in fertilized fields." *ACS Synthetic Biology* 10 (12): 3264–77.

[59] https://blog.pivotbio.com/press-releases/n-ovator

[60] https://www.agweb.com/news/crops/crop-production/study-finds-pivot-bio-provenr-40-increases-grower-revenue

[61] https://ec.europa.eu/eurostat/databrowser/bookmark/b18c1b79-f9fa-4d58-82da-de5d8ea4e383?lang=en

[62] https://blog.pivotbio.com/98-cleaner-corn

[63] https://agriculture.ec.europa.eu/common-agricultural-policy/agri-food-supply-chain/ensuring-availability-and-affordability-fertilisers_en#fertiliser-trade

[64] https://www.fertilizerseurope.com/fitfor55-ets-cbam/

[65] https://www.fertilizerseurope.com/fitfor55-ets-cbam/

[66] Calculation based on estimates from Ludemann et al. (2022) of synthetic fertiliser application per hectare for maize and maize crop area in 2018 across 20 countries in the EU.

[67] Ludemann, Cameron I., Armelle Gruere, Patrick Heffer, and Achim Dobermann. 2022. "Global Data on Fertilizer Use by Crop and by Country." *Scientific Data* 9 (501). https://doi.org/10.1038/s41597-022-01592-z.

Reduce food waste

NGTs can be used to reduce food wastage after crop products leave the farm gate — during transportation, processing, retail, and consumer use — in addition to decreasing on-farm wastage due to factors like pest damage. For example, researchers have developed a gene-edited mushroom that browns less after cutting (Dr Yinong Yang),[68] and a gene-edited potato with reduced browning (reduced browning potato, Toolgen Co., Ltd.[69]), both of which could help decrease food waste. Companies have also developed a genetically modified transgenic non-browning apple (Arctic® apples, Okanagan Specialty Fruits Inc.) and potato (J.R. Simplot Company[70]). Calyxt high-oleic soybean oil can also reduce food waste as it is more stable and lasts longer before spoiling.

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[68] https://www.aphis.usda.gov/biotechnology/downloads/reg_loi/15-321-01_air_response_signed.pdf

[69] https://www.aphis.usda.gov/aphis/newsroom/stakeholder-info/SA_By_Date/SA-2022/rsr-corn-potatoes

[70] https://www.aphis.usda.gov/brs/pdf/rsr/21-270-01rsr-review-response.pdf

Increase crop nutrition and improve flavour

NGTs can be used to improve crop nutrition and flavour. For example, gene editing has been used to decrease the level of unhealthy compounds in crops, including arsenic and cadmium in rice, and cyanide in cassava.[71] In addition, the company Pairwise recently released gene-edited mustard greens that contain less of a bitter compound, making the greens more appetising, which Pairwise hopes will be an alternative to less nutritious options like romaine lettuce. Sanatech Seed also released a gene-edited tomato with higher levels of a compound called GABA, which the company claims aids in relaxation and lowers blood pressure.

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[71] Pixley, Kevin V., Jose B. Falck-Zepeda, Robert L. Paarlberg, Peter W. B. Phillips, Inez H. Slamet-Loedin, Kanwarpal S. Dhugga, Hugo Campos, and Neal Gutterson. 2022. "Genome-Edited Crops for Improved Food Security of Smallholder Farmers." *Nature Genetics* 54: 364–67. https://doi.org/10.1038/s41588-022-01046-7.

Photo Source: Sanatech Seed Co.

Accelerate animal breeding and productivity growth

Genetic improvement, through selective breeding and genomic selection, has made livestock more feed-efficient, more productive, and more fecund, thus reducing the number of animals needed to meet milk, meat, and fibre demands globally. For example, the United States dairy industry reduced the amount of animal feed needed per kilo of milk by 17% between 2007 and 2017.[72] This comes on the heels of the United States dairy industry already reducing feed use per kilo by 77% between 1944 and 2007.[73] Similarly, the average milk yield per cow in the UK increased 88 kilo per year since 2004.[74] While these dairy cow improvements come from a combination of genetic selection, better nutrition, and management, researchers estimate about 55% of the yield increases are attributable to improved genetics.[75]

Likewise, disciplined genetic selection in United States poultry production has meat birds reaching higher market weights in fewer days[76] with increased feed conversions and hens laying 36 more eggs a year compared to 2002.[77] Likewise, non-organic, housed hens in the UK are predicted to lay 360 eggs per bird per year before 2030, an increase from current averages of about 295.[78] In the last three decades alone, genetic improvement has increased a sow's litter size by 37%,[79] with the United States' national average now above 11 pigs per litter. Between increased litter sizes, increased feed efficiency, and increased growth rates, genetic improvements continue to make animal protein production more efficient.

However, traditional selective breeding approaches rely on genetic variation within a population — requiring hundreds of animals and several years to see whole herd or flock transitions to desired traits. The rate of genetic change using selective breeding partially depends on the heritability of traits and the average age that the animals have offspring (the generation interval). Traits with greater heritability and animals with lower generation intervals enable faster genetic progress. The generation intervals for pigs, dairy cattle, and beef cattle are approximately 2 years, 3–4 years, and 5–6 years, respectively. And, with most desired traits between 20 and 50% heritable (for example, dairy milk yield is 25%), it could take 5 years to replace a milking herd with a small improvement in a single trait like yield.[80] If a farmer wants to select for multiple traits, it would take twice as long to replace the whole herd with the improved traits.

Fortunately, scientists have successfully sequenced some farm animal genomes, which enables faster and more precise genetic improvement.[81] Research and industry can use genomic editing tools to enhance animal

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[72] Capper, Judith L., and Roger A. Cady. 2020. "The Effects of Improved Performance in the U.S. Dairy Cattle Industry on Environmental Impacts between 2007 and 2017." *Journal of Animal Science* 98 (1): 1–14. https://doi.org/10.1093/jas/skz291.

[73] Capper, Jude L., Roger A. Cady, and Dale E. Bauman. 2009. "The environmental impact of dairy production: 1944 compared with 2007." *Journal of Animal Science* 87 (6): 2160–67.

[74] Garnsworthy, P.C. 2005. "Livestock yield trends: implications for animal welfare and environmental impact." In *Yields of farmed species: constraints and opportunities in the 21st century. Proceedings of a University of Nottingham Easter School Series, June 2004, Sutton Bonington, UK*, pp. 379–401. Nottingham University Press.

[75] Shook, G.E. 2006. "Major advances in determining appropriate selection goals." *Journal of Dairy Science* 89 (4): 1349–61.

[76] https://www.nationalchickencouncil.org/about-the-industry/statistics/u -s-broiler-performance/

[77] https://unitedegg.com/facts-stats/#:~:text=The%20daily%20rate%20of%20lay,the%20graph%20to%20the%20right

[78] Garnsworthy, P.C. 2005. "Livestock yield trends: implications for animal welfare and environmental impact." In *Yields of farmed species: constraints and opportunities in the 21st century. Proceedings of a University of Nottingham Easter School Series, June 2004, Sutton Bonington, UK*, pp. 379–401. Nottingham University Press.

[79] https://quickstats.nass.usda.gov/results/0662142D-3613-352D-8041-16CE59B7B19E

[80] Field, Thomas G., and Robert W. Taylor. 2020. *Genetic Change Through Selection In Scientific Farm Animal Production: An Introduction to Animal Science*, 12th edition. Pearson.

[81] Groenen, Martien A. M., Alan L. Archibald, Hirohide Uenishi, Christopher K. Tuggle, Yasuhiro Takeuchi, Max F. Rothschild, Claire Rogel-Gaillard, et al. 2012. "Analyses of pig genomes provide insight into porcine demography and evolution." *Nature* 491 (7424): 393–98.

performance and continue to reduce the costs of production. For example, heritability and selection differential delays in genetic progress can be overcome through genome editing. Genome editing is already showing the potential for positive impacts on farm animal production. For both cattle and sheep, the gene connected to muscling can be targeted so that offspring have increased lean muscle growth.[82] Likewise, sequenced genomes are being used to improve animal health and wellbeing while aligning agricultural production goals with environmental outcomes.

Improve animal disease resistance

Breeding for disease resistance is becoming more important than ever with foreign animal diseases destroying whole herds and flocks. At the same time, domestic animal diseases remain a costly nightmare to animal protein producers. One such disease — Porcine Reproductive and Respiratory Syndrome (PRRS) — is often cited as the most economically devastating disease to the swine industry worldwide. The PRRS virus leads to stunted growth and reproductive failure including foetus mummification. In surveyed European countries, PRRS was estimated to have cost pig producers €1.5 billion.[83] Protecting pigs from disease is imperative in the EU. In fact, the European Union is the world's second largest producer and number one exporter of pork,[84] with 142 million pigs in 2021.[85] More than 25 years of global investment in PRRS prevention and treatment was unable to halt the disease's detrimental effect on productivity.

Fortunately, genome editing to increase livestock disease resistance is no longer theoretical.

In 2017, researchers in the United Kingdom used CRISPR/Cas9 editing to generate pigs resistant to the PRRS virus.[86] Presently, this genome editing approach is the only option that creates complete resistance to PRRS virus infection — rather than prevention mechanisms like biosecurity and vaccination — thus increasing animal welfare and mitigating billions in financial losses.

Regulating gene editing in livestock similarly to GMOs would have large costs. One study estimated that preventing the commercial introduction of PRRS virus-resistant pigs in the EU would cost producers and consumers up to $29 billion.[87] Likewise, delaying introduction of genetically modified mastitis-resistant cows by ten years would cost up to $2.54 billion, while preventing commercialisation would cost up to $7.4 billion.

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[82] Proudfoot, Chris, Daniel F. Carlson, Rachel Huddart, Charles R. Long, Jane H. Pryor, Tim J. King, Simon G. Lillico, et al. 2015. "Genome edited sheep and cattle." *Transgenic Research* 24: 147–53.

[83] https://www.pig333.com/articles/prrs-cost-for-the-european-swine-industry_10069/

[84] https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/652044/EPRS_BRI(2020)652044_EN.pdf

[85] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agricultural_production_-_livestock_and_meat#Livestock_population

[86] Burkard, Christine, Simon G. Lillico, Elizabeth Reid, Ben Jackson, Alan J. Mileham, Tahar Ait-Ali, C. Bruce A. Whitelaw, and Alan L. Archibald. 2017. "Precision engineering for PRRSV resistance in pigs: Macrophages from genome edited pigs lacking CD163 SRCR5 domain are fully resistant to both PRRSV genotypes while maintaining biological function." *PLoS Pathogens* 13 (2): e1006206.

[87] Van Eenennaam, A.L., F. De Figueiredo Silva, J.F. Trott, and D. Zilberman. 2021. "Genetic engineering of livestock: the opportunity cost of regulatory delay." *Annual Review of Animal Biosciences* 9: 453–78. https://www.annualreviews.org/doi/full/10.1146/annurev-animal-061220-023052#_i18.

Increase livestock nutrient use efficiency

Reactive nitrogen and phosphorus leaching from agricultural production systems — including livestock — are one of the main causes of eutrophication in waterways.[88] In fact, 73% of agriculture's impact on water pollution in Europe has been attributed to livestock manure's nitrogen and phosphorus.[89]

Genetic modification and editing of animals has the potential to reduce nutrient use and leaching in several ways.

Genetic modification can make pigs more nitrogen and phosphorus efficient. Pigs, as monogastrics, lack the phytase enzyme that would make phosphorus in plants available for metabolism. As such, pigs cannot utilise most of the phosphorus from corn and soy in their diets — instead, it gets excreted in feces in high levels. To address this problem, researchers produced a transgenic pig expressing the phytase enzyme gene, resulting in a 75% reduction in excreted phosphorus.[90] The transgenic pigs not only excreted less nitrogen and phosphorous, but also grew faster.[91] Additionally, if these transgenic pigs — or a similar genome-edited version —were commercialised, they would help EU pig producers reduce their cost of production substantially. In 2019, Spain, Germany, and France — the EU's top three producing member nations — had production costs of €1.40, 1.54, and 1.47 per kilo of carcass, respectively.[92] At the same time, the United States' cost of production was only €1.06 per kilo of carcass. To remain competitive as a top producer and exporter of pig meat, the European Union should consider agricultural biotechnologies to reduce costs of production. Without the commercialisation of pigs with the phytase enzyme, producers are reliant on costly supplemental phosphorus and supplemental phytase enzymes to meet the dietary phosphorus requirements for growth, gestation, and lactation. Genetic technologies provide a much-needed tool to close the loop in livestock nutrient cycling — improving both air and water quality.

Gene editing can also change other traits that influence nutrient use, such as the sex of animals. Female pigs require fewer grams of protein than their male counterparts to gain the same amount of lean meat. If gene editing enabled sow farms to birth all-female litters, then growing and finishing farms could feed less nitrogen without impacting weight gain, thereby reducing nitrogen in manure and water pollution. Moreover, all-female pig litters would avoid the need to castrate young male pigs — providing animal welfare benefits.

Gene editing to influence the sex of poultry can also reduce nutrient excretion and pollution. Most meat birds are sold as mixed-sex batches, yet males require less dietary energy per gramme of body weight gain compared to females. Compared to all-male batches, these mixed-sex batches generate more feed waste and nutrient excretion — both of which result in higher levels of nitrogen and phosphorus in poultry litter. Given how difficult and costly it is to separate birds by sex after hatching, developing all-male strains through genome editing is a viable solution to excess nutrient loss, thus reducing poultry production's negative environmental impact.

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[88] https://environment.ec.europa.eu/topics/water/nitrates_en

[89] Leip, Adrian, Gilles Billen, Josette Garnier, Bruna Grizzetti, Luis Lassaletta, Stefan Reis, David Simpson, et al. 2015. "Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity." *Environmental Research Letters* 10 (11): 115004.

[90] Golovan, Serguei P., Roy G. Meidinger, Ayodele Ajakaiye, Michael Cottrill, Miles Z. Wiederkehr, David J. Barney, Claire Plante, et al. 2001. "Pigs expressing salivary phytase produce low-phosphorus manure." *Nature Biotechnology* 19 (8): 741–45.

[91] Golovan, Serguei P., Roy G. Meidinger, Ayodele Ajakaiye, Michael Cottrill, Miles Z. Wiederkehr, David J. Barney, Claire Plante, et al. 2001. "Pigs expressing salivary phytase produce low-phosphorus manure." *Nature Biotechnology* 19 (8): 741–45.

[92] https://www.pig333.com/articles/what-were-production-costs-on-pig-farms-in-2019_16989/

What should the EU do going forward?

In order to access benefits of NGTs to humans and the environment, support development of the EU bioeconomy, and increase international competitiveness, the bloc should act to prevent regulatory and public opinion barriers from blocking the use of NGTs in the agricultural, food, industry, and health sectors. Actions should involve implementing more permissive regulations for gene-edited plants than for GMOs, allowing the use of gene-edited microbes in agriculture, and beginning to approve biotech food products. We estimate that up to €171–335 billion in annual benefits to humans and the environment are at stake.

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