Master's Thesis – Master Sustainable Business and Innovation

The rise of gene-editing technologies:

Threats and opportunities for ecological sustainability.

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Summary

Gene-editing technologies can be defined as a emerging technologies and promise to solve problems in relation to health, sustainability, poverty and agricultural productivity.

However, no studies have been done yet on the possible impacts of gene-editing technologies on ecological sustainability. This thesis aims to fill this gap by researching scientists' expectations of gene-editing on ecological sustainability. In this thesis, ecological sustainability is defined according to the Core Set of Indicators (CSI) of the European Environment Agency (EEA).

Thirty scientists with expertise in both gene-editing and ecological sustainability were interviewed. The findings are grouped per thematic theme as defined by the CSI of the EEA.

The results show that scientists expect both threats and opportunities for gene-editing in relation to ecological sustainability. The findings could be used as a building block in creating a more comprehensive forecast of the possible impacts of gene-editing technologies on ecological sustainability. Suggestions for further research are done with regards to interviewing other stakeholders than scientists, because the success or failure of a technology is never dependent upon one actor only.

Table of content

1. Introduction

Gene-editing technologies offer uncertain, but promising and economically rewarding opportunities to businesses (Egelie, Graff, Strand & Johansen, 2016). Gene-editing technologies are in their infancy but are being developed quickly and applied in various fields, most notably the healthcare industry (Fellmann, Gowen, Lin, Doudna & Corn, 2016). Despite the growing attention to gene-editing, it is still very unclear what the impacts of the technologies will be on ecological sustainability. Whereas the impact of gene-editing on the inheritance of altered genes in plants (Zhang et al., 2014) and the usefulness of gene-editing in human stem cells (Lombardo et al., 2008) has already been subject to debate, so far, no studies or reports exist that interrogate the relation between gene-editing and ecological sustainability.

Gene-editing promises to solve problems in relation to sustainability, poverty and agricultural productivity. In contrast to previous DNA-changing techniques, gene-editing technologies allow for much more specific alterations and deletions of the genome by deleting, adding or substituting nucleotides (Howard et al., 2017). In this way, the phenotypes of species can be altered very precisely. Examples of these technologies are Zinc Finger Nucleases (ZFN), Transcription Activator-Like Effector Nucleases (TALEN) and Clustered Regularly-Interspaced Short Palindromic Repeats (CRISPR). Especially since the discovery of CRISPR in 2012, a technique that allows scientists to edit genomes in a very quick and targeted way, a lot of promises have been made about the solutions gene-editing technologies can have for various global problems.

For example, laboratory research has already shown that gene-editing can be applied to enhance public health by making male mosquitoes sterile, in order to combat dengue and malaria (Gantz et al., 2015; Hammond et al., 2016; Burt et al., 2018), and other researchers have applied gene editing to modify maize species in order to increase agriculture productivity (Baltzegar et al., 2017; Scott et al., 2017). And much more is promised. The technique is so precise that researchers can target one specific genetic element and change the inheritance rate, so that the altered genetic element will eventually be present in 100% of the population, a so-called gene drive. In this way, entire species could be eliminated. This technique could be applied in wildlife conservation, for example to suppress invasive mouse populations on islands to protect native birds (NASEM, 2016).

However, gene-editing also raises several questions about its potential ecological impact and societal desirability. What effects does eating genetically edited insects or animals have on animals or humans? (Caplan, Parent, Shen & Plunkett, 2015) What impact does gene-editing have on animal welfare? (Ledford, 2015) Are we allowed to eradicate an entire species to control disease vectors? (Oye et al., 2014) Who is responsible for putting biosafety measures into place for introducing edited organisms into the environment? (Esvelt, Smidler, Catteruccia & Church, 2014). Does the public play a role in the decision-making process around the deployment of genetically-edited organisms? (Caplan, Parent, Shen & Plunkett, 2015). These are all questions to be considered when debating about the desirability of gene-editing applications.

The debate around genetically modified crops and organisms is not new. In the past decades, there has been a fierce debate around the pros and cons of genetically modified plants (Wolfenbarger & Phifer, 2000). What makes the debate around gene-editing different is that the technique no longer requires the insertion of foreign DNA into the organism's genome (Caplan, Parent, Shen & Plunkett, 2015). Various scientists have therefore called for a change in regulation concerning the use of gene-editing technologies. Some scientists argue for less stringent regulations concerning the use of gene-editing in crops (Urnov, Ronald &

Carroll, 2018), while others highlight that using gene-editing in human cells should be more regulated or even temporarily prohibited. For example, in 2015, scientists called for a temporary moratorium on genetic editing of the human embryo (Lanphier, Urnov, Haecker, Werner & Smolenski, 2015). In their eyes, a prohibition to further develop the technology was necessary, because of the life-controlling possibilities that this technology promises. For example, designing baby embryos to have blue eyes or blond hair. And in 2016, scientists called for a moratorium on gene-drive technologies, due to the irreversible effects that gene-edited organisms may have on the environment (Callaway, 2016). Both calls were rejected, but the debate around gene-editing technologies still persists (Cyranoski & Reardon, 2015).

Besides the ethical issues of gene-editing when using it to edit the human germ line, one of the main points of contention in the debate on gene-editing is the impact it might have on the environment (Caplan, Parent, Shen & Plunkett, 2015). Even though gene-editing technologies are relatively new and edited organisms have not been released in the environment yet, it is important to start thinking about the potential impacts of such a release (Esvelt & Gemmell, 2017). Professor Lunshof, a bioethicist from Groningen University, warns us that the increasing use of CRISPR to modify the genomes of wild populations might potentially have damaging and irreversible effects on ecosystems, unless they are contained and well-regulated (Lunshof, 2015). She explains that compared to human applications of CRISPR, the possibility of permanent ecosystem modification is much more troubling, because 'such disruption has more severe, complex, system-level consequences, and the breadth of its impact and the duration of its effects are hard to mode' (Lunshof, 2015, p 127).

The Brundtland report defines sustainability as 'meeting the needs and aspirations of the present without compromising the ability to meet those in the future' (Report of the World Commission on Environment and Development: Our Common Future, 1987, p 39).

Since the duration of the modifications that gene-editing organisms bring about in an ecosystem is hard to model (Lunshof, 2015), future generations might be negatively affected if the technology is not well-regulated today. Therefore, it is important to forecast the potential impacts of gene-editing applications on ecological sustainability.

Very little is known about the potential impacts of gene-editing on ecological sustainability as of now. A lot of studies have been done on the expectations of the public in relation to GMOs (Gaskell, 1999; Nelson, 2001; Savadori et al., 2004), the role of the food industry in the acceptability of GMOs (Kuznesof & Ritson, 1996; Schmitz, 2004) and the potential impact of GMOs on health (Panchin & Tuzhikov, 2016) and the environment (Dale, Clarke & Fontes, 2002). With regards to gene-editing and ecological sustainability, there have some studies that show that the technology might have positive impacts on the environment through genetic pest management (Leitschuh et al., 2017) and studies that warn us for the possible unintended negative consequences of releasing gene-edited organisms in the environment (Hayes et al., 2018). But overall, no study has been done that researches scientists' expectations of gene-editing in relation to ecological sustainability.

The promises, visions and expectations of scientists working with the gene-editing technologies are a valuable source of information at our disposal to research the potential impacts of the gene-editing technologies on ecological sustainability, because they are at the forefront of technology-development, meaning they are in a good position to see the potential consequences of the technology (Aebersold, Hood & Watts, 2000). And because of the performative function of expectations (Van Lente, 2012), the expectations scientists hold is one of the factors that inform the future work they will do. Interviewing scientists can therefor give insight into the direction the technology might evolve, making it possible to forecast potential opportunities and threats of gene-editing for ecological sustainability.

The aim of this thesis is to contribute to the understanding of the potential opportunities and threats of gene-editing in relation to ecological sustainability. The research question is: what do scientists expect to be the main potential threats and opportunities of gene-editing technologies for ecological sustainability? In order to research the connection between gene-editing technologies and ecological sustainability, semi-structured interviews will be conducted with scientists who are working on or with the technology. The scientists to be interviewed will be chosen based on their expertise both in the field of gene-editing and sustainability.

The concept of ecological sustainability will be defined by drawing indicators from the Core Sustainability Indicators (CSI) that have been developed by the European Environment Agency (EEA) and presented in its 2014 report (EEA, 2014). In this report, the EEA revised a core set of environmental indicators which were structured into six environmental thematic areas: air pollution, transport and noise; climate change and energy; freshwater resources; marine and maritime; biodiversity and ecosystems; and waste and resources. Even though the methodology behind these indicators is not applicable to gene-editing since no data exists yet on the release of gene-edited organisms, the environmental areas are useful because a) they give a comprehensive overview of the most important environmental aspects, b) they cover the most pressing environmental issues the EU is dealing with (EEA, 2014) and c) they allow for a systematic overview of the expectations of scientists on these different environmental areas.

Since the success or failure of a technology is dependent upon more actors than only scientists, suggestions for further research are done that could focus on other stakeholder than scientists, like policy makers, special interest groups and the general public, who all play a role in the development, dispersion and acceptability of a technology in society (Voytas & Gao, 2014).

In the following section, the theoretical framework drawn from the Core Set of Indicators from the European Environment Agency will be presented.

2. Theory

Nations are becoming increasingly dependent on the rate of technological innovation to be wealthy and prosperous (Cozzens et al., 2010). Radically new technologies can become a powerful competitive force that allow for the creation of entirely new industries (Hamilton, 1985). Schumpeter described the transformational power of emerging technologies as a force of 'creative destruction', which can pose a threat to existing market equilibria (Schumpeter, 1934). But emerging technologies can also disrupt ecological equilibria, oftentimes years after their initial implementation (Widmer et al, 2005; Robinson, 2009). When uncertainty around the possible impacts of the new technologies is high, the urgency of assessing the possible impacts of the emerging technology increases (Robinson, Huang, Guo & Porter, 2013).

Gene-editing technologies are tools that allow for precise and specific gene engineering. Even though there are many different genome-editing tools, the most well-known and most adopted one among scientists is the CRISPR/cas9 system (Doudna & Charpentier, 2014). In contrast to zinc finger nucleases (ZFNs) and transcription activator–like effector nucleases (TALENs), two other gene-editing technologies 'which require substantial protein engineering for each DNA target site to be modified, the CRISPR-Cas9 system requires only a change in the guide RNA sequence' (Doudna & Charpentier, 2014, p 3). Because of this comparative advantage, the system has been widely adopted by the scientific community to change, edit or modify the genes in organisms (Doudna & Charpentier, 2014).

Gene-editing technologies can be seen as emerging technologies. Cozzens et al (2010) analyzed the definitions of emerging technologies used in nearly 2000 articles in the literature of technology management, economics and public policy and summarized them in four-fold: 'a) fast recent growth; b) in the process of transition and/or change; c) market or economic potential that is not exploited fully yet; d) increasingly science-based.' (p. 365-6). When we look at gene-editing technologies, they fit the label of 'emerging'. There has been a) an exponential growth in the number of articles published on gene-editing technologies (Elsevier, 2016), b) the technologies are constantly being refined, especially since the invention of CRISPR a whole new set of organisms can be modified at a cost-effective rate (Ledford, 2016a), c) there are huge profits to be made with gene-editing technologies (Contreras & Sherkow, 2017) and d) academia plays a big role in the development of the technologies (Ledford, 2016b). Gene-editing technologies thus fit the definition of emerging technologies.

It is important to assess potential consequences of emerging technologies at an early stage of development, even if those consequences are still uncertain (Robinson, Huang, Guo & Porter, 2013). The rationale behind this is that it is desirable to forecast developments when they are still adaptable (Lucivero, Swierstra & Boenink, 2011). Different forms of technology assessment (TA) have been developed to research the potential impacts of emerging technologies at an early stage, and scholars have contributed to this field with a variety of studies applying different adaptations of TA. Examples of adaptations are Constructive TA (Jacobson, Rip, Misa & Schot, 1997), Real Time TA (Guston & Sarewitz, 2002) and Midstream Modulation (Fisher, Mahajan & Mitcham, 2006).

Forecasts applying TA have an illusory object: an emerging technology that mainly only exists yet in the visions, promises and expectations (Lucivero, Swierstra & Boenink, 2011). These may vary from how the technology will develop in the lab to what business opportunities the technology will present and how it will benefit the quality of human life. Unfortunately, many studies have pointed out that these promises and visions are often incorrect. Visions can be biased by the pressure felt to mobilize resources (Brown & Michael, 2003; Borup, Brown, Konrad & Van Lente, 2006) or might be false or incomplete (Deyo, Patrick, 2005). Technologies that leave the laboratory and enter the commercial sphere simply turn out to develop in unexpected ways and deliver more or less than expected (Lucivero, Swierstra & Boenink, 2011). Nonetheless, when studying the potential impacts of emerging technologies, these visions, promises and expectations cannot be avoided, and so a way has to be found to assess them as accurately as possible. How do we accurately assess the impacts of emerging technologies on ecological sustainability?

It is important to realize that emerging technologies not only potentially disrupt the market equilibrium but may also have impacts on ecological sustainability. An example of this is agrofuels. Initially these were seen as the perfect alternative to fossil fuels (Hill, Nelson, Tilman, Polasky & Tiffany, 2006), but soon turned out that in order to meet the demand of the crops needed to produce fuel, large-scale monoculture production systems had to be put in place (Altieri, 2009). This led to deforestation and the rearrangement of land dedicated to the production of food crops, as well as a rise in the utilization of agrochemical inputs like herbicides and fertilizers, creating huge negative environmental impacts (Altieri, 2009).

A second example of the ecological impacts of an emerging technology can be seen in the poisonous effects of e-waste. Electronic devises are often brought as game-changing devises (Lewotsky, 2007), but e-waste contains potential environmental containments and is disposed of in landfills (Robinson, 2009). Scholars have found this could among others have serious impacts on the soil (Leung, Luksemburg, Wong & Wong, 2007), river sediments (Ni, Zeng, Tao & Zeng, 2010), air quality (Li, Jiang, Wang, Wang & Zhang, 2008) and the health of birds (Luo et al., 2009). However promising technologies might be when they are presented to the world, unintended negative effects on the environment occur when their potential ecological impacts are not thoroughly reviewed (Lunshof, 2015).

There are very good methods for assessing environmental impacts. For example, Life Cycle Assessment (LCA), which is a tool used to measure the impact of a product throughout its life-cycle, from raw material acquisition to waste management (Finnveden et al., 2009). This tool can be very comprehensive and helps evaluate the magnitude of the potential environmental impacts of the studied product or process (Muñoz et al., 2008). The drawback of this tool for the purpose of this study is that in order to perform an LCA, a lot of data is required to come to a sound conclusion (Finnveden et al., 2009). Gene-editing is an emerging technology, which means that it has not been applied yet in all its potential applications. We cannot perform an LCA when quantitative data is lacking (Guo & Murphy, 2012). Therefore, LCA as an environmental impact assessment tool is unfit for the purpose of this study.

Another method used to assess environmental impacts is the Environmental Sustainability Index (ESI). It is an index that is used to evaluate a nation's sustainability (Siche, Agostinho, Ortega & Romeiro, 2008), and based upon a set of sixty-eight basic indicators, which are summed up in twenty core indicators, among others air quality, water quality, biodiversity, reducing population growth and capacity for debate (Jha & Bhanu Murthy, 2003). While the ESI allows for a very comprehensive comparison of countries' practices to create a sustainable society (Siche, Agostinho, Ortega & Romeiro, 2008), the drawback of this framework for the purpose of this study is that it integrates nature and society, meaning that it does not allow to focus the research solely on the environmental pressures arising from certain human activities (Esty et al., 2005). The focus of this thesis is on potential impacts of gene-editing on ecological sustainability, meaning we need a framework that allows us to focus on the ecological impacts.

The framework chosen in this study comes from the Core Set of Indicators (CSI) of the European Environment Agency (EEA). The EEA is an agency from the EU whose task it is to provide ‘sound, independent information on the environment’ (“About us,” 2018). The EEA maintains a set of 137 indicators, grouped into thirteen environmental themes. From these 137 indicators, the EEA selected an inner core (or CSI), aimed ‘to produce an indicator set with a more balanced structure and improved alignment with current policy priorities’ (EEA, 2014, p 28). The CSI consists of 42 indicators, structured into six thematic areas. These areas integrate the economic sectors that the EEA considers to be the main sources of environmental pressures, namely agriculture and forests, fisheries, energy and transport (EEA, 2014).

In order to define to measure the potential impact of gene-editing on ecological sustainability, we will look at the following six thematic areas (see Table 1 for a list of all the EEA Core Set of Indicators):

a) Air pollution, transport and noise. This thematic area covers environmental indicators relating to the emission of main air pollutants (ozone precursors like nitrogen oxide (NO_x), and acidifying substances like nitrous oxide (N_2O)), passenger and freight transport demand, use of cleaner and alternative fuels, and ambient noise limit values for road traffic. Under this section, carbon dioxide and methane emissions are not considered. These will be discussed in the ‘climate change and energy’ section.
b) Climate change and energy. This thematic area covers indicators relating to climate change mitigation (greenhouse gas and fluorinated gas emissions, and atmospheric

greenhouse gas concentrations), climate change impacts (global and European temperature, cryosphere[1] trends for European glaciers and sea ice) and energy (share of renewable energy in final energy consumption).

c) Freshwater resources. This thematic area covers environmental indicators relating to the use of freshwater resources, the quality of freshwater resources, and pressures on freshwater resources deriving from the agricultural use of nitrogen and pesticides.

d) Marine and maritime. This thematic area covers indicators relating to the water quality of transitional, coastal and marine water; the status of marine fish stocks, the sea surface temperature and the global and European sea level rise.

e) Biodiversity and ecosystems. This thematic area covers environmental indicators relating to the abundance and distribution of species, the loss and degradation of ecosystems, and the status of forests.

f) Waste and resources. This thematic area covers indicators relating to waste generation, waste recycling, energy efficiency and the decoupling of resource use from environmental pressures and impacts. This last indicator relates to the reduction of material consumption, essentially 'doing more with less' ("Resource efficiency", 2015, February 18).

The exact methods to measure the CSI cannot be used for gene-editing because it is an emerging technology and its impacts can only be measured once the technology has been applied and released in the environment. Nonetheless, the indicators can still be used as a valid theoretical framework for the environmental impact of gene-editing, because a) they

[1] The cryosphere is that part of the earth that is either covered in water that is in solid form (ice, snow) or is frozen ground (the permafrost).

give a comprehensive overview of the most important environmental aspects, b) they cover the most pressing environmental issues the EU is dealing with (EEA, 2014) and c) they allow for a systematic overview of the expectations of scientists on these different environmental areas.

In order to measure the potential impact of gene-editing on the core set of indicators, other methods should be used. These will be discussed in the methodology section.

Table 1. EEA Core Set of Indicators (CSI).

Thematic Area and Topic	Indicator name
A. Air pollution, transport and noise	
Air pollution	Emissions of main air pollutants.
	Exceedance of air quality limit values in urban areas.
	Exposure of ecosystems to acidification, eutrophication and ozone.
Transport	Passenger and freight transport demand.
	Use of cleaner and alternative fuels.
Industry	Pollutant releases to air, water and waste from industrial facilities.
Noise	Population exceeding ambient noise limit values (for road traffic).
B. Climate change and energy	
Climate change mitigation	EU and national total greenhouse gas emission trends and projections.
	Atmospheric greenhouse gas concentrations.
	Production, consumption and emissions of fluorinated gases.
Climate change impacts	Global and European temperature.

	Cryosphere trends for European glaciers and sea ice.
Energy	Overview of European energy system.
	Share of renewable energy in final energy consumption.
C. Freshwater resources	
Water resources/ water scarcity and drought	Use of freshwater resources.
Freshwater ecosystems	Trends in ecological status.
Water pollution and quality	Oxygen consuming substances in rivers.
	Nutrients in freshwater.
Water and health	Bathing water quality.
Climate change impacts on water	Climate change impacts on water.
Pressures on water	Pressures on water.
D. Marine and maritime	
Transitional, coastal and marine water quality	Nutrients in transitional, coastal and marine waters.
	Chlorophyll in transitional, coastal and marine waters.
	Hazardous substances in marine organisms.
Fisheries	Status of marine fish stocks.
	Fishing fleet capacity.
Climate change	Sea surface temperature.
	Global and European sea level rise.
Thematic Area and Topic	**Indicator name**
E. Biodiversity and ecosystems	

Status and trends of the components of biological diversity Thematic Area and Topic	Species and habitats of European interest.
	Designated areas.
	Abundance and distribution of selected species.
Threats to biodiversity: Habitat loss and degradation	Land take.
	Fragmentation of habitats and ecosystems.
Sectors – agriculture and forests	Agricultural areas under Natura 2000.
	Forest: growing stock, increment and fellings and deadwood.
F. Waste and resources	
Waste generation	Waste generation.
Waste recycling	Waste recycling.
Waste diversion from landfill/ disposal	Diversion of waste from landfill.
Household consumption	Household environmental pressure intensity.
Energy efficiency	Total primary energy intensity.
Decoupling of environmental pressures	Decoupling of resource use from environmental pressures.
Decoupling of environmental impacts	Decoupling of resource use from environmental impacts.

3. Methodology

Emerging technologies are characterized by uncertainty and ambiguity because their full potential lies in the future (Fleischer, Decker & Fiedeler, 2005). This means that it is not possible to predict, but only to explore the possible impacts of the technology. Well-established methods that rely on ex-post assessment, like Life Cycle Assessment, are therefore unfit for assessing the sustainability impacts of gene-editing technologies and can only be performed at later stages of technology development (Fleischer, Decker & Fiedeler, 2005). In the case of gene-editing technologies, a method is needed that enables us to systematically explore the impacts of the technology on the six thematic areas of the EEA's Core Set of Indicators.

a. Research Design

Expert interviews are a fitting method for exploring the potential impacts of emerging technologies. Scientific experts often have a vision of the potential impacts that reach further than the conclusions they write in their papers (Lucivero, Swierstra & Boenink, 2011). In scientific articles, outcomes of scientific research are often presented as facts, while interviewing the authors of the articles offers an interesting access to 'expectations, uncertainties, challenges, controversies and doubts' (Lucivero, Swierstra & Boenink, 2011, p 141). In this way, we can uncover what is covered-up in more public arenas. For example, preliminary findings surrounding field trials of the release of gene-edited mice on an island might get published in journals (NASEM, 2016), but value questions about what an acceptable level of risk is and what negative consequences could arise due to the development of gene-editing technologies are usually not explicitly mentioned in papers. Interviewing experts can give us a unique opportunity to inquire further about personal views that are not likely to be published but are nonetheless crucial to understand the debate around the potential impacts of the emerging technology. But how can we assess the quality of expert's expectations and promises on emerging technologies?

When engaging in a reflection on the potential impacts of emerging technologies, it is important to explore the quality of promises and expectations (Lucivero, Swierstra & Boenink, 2011). To assess promises and expectations on emerging technologies, Lucivero, Swierstra and Boenink propose to focus 'on statements on technological feasibility, societal usability, and desirability of the expected technology' (2011, p 129). The focus on technological feasibility is important, because of the tendency to begin an analysis by hypothesizing futuristic technologies and to immediately draw conclusions that present huge existential issues raised by the emerging technology. Nordmann calls this the 'if and then fallacy', which occurs when a researcher adopts the expert's expectations without a critical view on its content (Nordmann, 2007). The resulting conclusions are then based on an unrealistic scenario, leading to 'mere speculations' (Grunwald, 2010, p 95).

One could ask: should the researcher not simply trust the scientific expert? Why not simply believe the scientists who are working on gene-editing and gene-drives and take their expectations for granted? Lucivero et al. (2011) point out that there are two reasons for distrust. The first one, is that history shows that many promises made by scientists do not materialize. And second, the sociology of expectations makes clear that claims are often made strategically to get access to resources and funds (Brown and Michael, 2003). When analyzing the plausibility of expectations, one thus has to keep in mind the aims of the actor who states the expectation and the audience he has to reach (Lucivero, Swierstra & Boenink, 2011). This can be done by asking oneself questions like 'What is the background of the interviewee?', 'Who is the audience?' and 'What strategic aim could the interviewee have to have to express this expectation?'.

Besides the technological feasibility of an emerging technology, we should also assess expert's claims on the technology's usability and desirability. The problem is that for these aspects, we cannot analyze their objective reality or truth (Lucivero et al., 2011). However, we can 'analyze to what extent and at which conditions a specific audience, holding a more or less specific knowledge on the topic, considers these expectations plausible' (Lucivero et al., 2011, p 133). Even if something is expected to be technically possible, there might be impossible social conditions presumed in the expectations. Future visions are often built on assumptions of how society works. Script theory (Akrich, 1992) refers to these assumptions as the 'fictive script' (De Laat, 2000). The task of the researcher is to uncover the fictive script of an emerging technology by inquiring in a very detailed manner how the interviewee envisions the context of the application of the technology and what role different actors play in the success or failure of the technology (Lucivero et al., 2011).

A further way to analyze the usability of the emerging technology, would be by investigating how plausible the intended audience of the emerging technology finds the promises and expectations. The knowledge and views of for example the general public can be collected with methods that have been developed by 'Constructive Technology Assessment' (CTA). The focus of this thesis is to show the expectations of scientists working on gene-editing, so the general public is not included in the data gathering process, but an area of further research could be to include the voice of other actors that may be using the applications of gene-editing technologies in the future. By sharing and discussing the visions of scientists with the intended users and other stakeholders, it would become possible to see where the scientists' views collide with the views of other stakeholders and users (Lucivero et al., 2011). This would enrich the expectations created around an emerging technology.

The third dimension of analyzing the quality of expectations is desirability (Lucivero et al., 2011). Assessing the desirability of an emerging technology builds upon the previous two dimensions of feasibility and usability but adds a normative component to the analysis. The question becomes how the potential impact of the technology is normatively evaluated by the audience.

The normative evaluation of an emerging technology is likely to differ among audiences with a different normative stance. This insight comes from the approach of Technology Assessment known as 'Vision Assessment' (Grin & Grunwald, 2000). Vision Assessment states that for every expectation, promise and vision of an emerging technology, certain norms and values of a good life are implied. To improve the process of carefully weighing the options around the development of an emerging technology, the normative views of different audiences and stakeholders should be consulted. This is because 'the allegedly universal benefits that a technology is supposed to bring about are, de facto, not unanimously shared or understood (Lucivero et al., 2011, p 136). The focus of this thesis is on highlighting the normative view of scientists on the impacts of gene-editing on ecological sustainability. Future studies building on this thesis, could diversify the set of stakeholders in order to compare those to the normative visions of scientists.

A way to imagine potential future controversies of the desirability of the emerging technology is by referring back to moral arguments known from earlier debates on emerging technologies (Swierstra & Rip, 2007). Earlier debates often show patterns of arguments that can be used to speculate on how debates on emerging technologies could develop (Swierstra & Rip, 2007). In the case of gene-editing, we could draw on arguments around the desirability of GMOs. For example, arguments that GMOs hold the key to solve global environmental problems (Buechle, 2001), that GMOs are safe for human health (Herman & Price, 2013) and that GMOs are more profitable to the farmer than conventional crops (Marra et al, 2002). The reality is that the environmental benefits of GMOs are mixed (Cuhra, 2015), that the public sees risks in consuming GMO food (Bredahl, Grunert & Frewer, 1998; Kinderlerer, 2000; Nelson, 2001), that there is no scientific consensus on GMO safety (Hilbeck et al., 2015), that the yield benefits for the farmer are not always clear (Xia, Chen, Wang & Lu, 2010) and are unevenly spread among rich and poor (Sedjo, 2006). History does not simply repeat itself, but it does provide examples that are an important ingredient in the reflection on the potential impacts of an emerging technology. When assessing promises and expectations of scientists on gene-editing, referring back to the discussion on GMO could help envision the plausibility of their expectations.

To sum up, visions and promises of emerging technologies need to be analyzed on different dimensions. The feasibility and usability claims of the interviewees need to be assessed because of the potential of biased and uncritical promoting of the possibilities, while desirability claims need to be assessed due to the implied normative viewpoints an interviewee might hold, viewpoints that might not necessarily still be the same in the future. By exploring these different dimensions, it becomes possible to assess the plausibility of expectations.

b. Data collection

Thirty scientists from all over the world were interviewed (see table 2 for list of interviewees). In order to find the top researchers with knowledge on both gene-editing and ecological sustainability as defined by the six thematic areas of the European Environment

Agency, word clouds were created around these six thematic areas (see appendix 2). The words for the word clouds were deducted from the description of each Core Environmental Indicator given by the EEA in their 8th Technical Report of 2014 (EEA, 2014).

Each word of the word cloud was combined with either 'CRISPR*', 'gene edit*', or 'gene drive*'. These three words were chosen because they were thought to be the main words used in papers on gene-editing. 'Genome edit*' was not included in the searches, because of the overlap with searches done with 'gene edit*'. In total, 141 different searches were done via Web of Science. Web of Science is an online citation search service that combines multiple databases of scientific research and allows for interdisciplinary searches. It is a suitable database because next to connecting almost 33000 journals ("Web of Science"), the service offers various ways of ranking the search results, among others by times cited and date of publication.

The results were first sorted by times cited. The abstracts of the top-50 cited papers of each search were analyzed to see whether they contributed to an understanding of gene-editing in relation to one of the six ecological sustainability fields. All papers dealing with gene-editing and ecological sustainability were then grouped per thematic area in a document, to ensure that all indicators were covered.

To make sure that recent studies that had not had the chance to be cited very often were also considered, the top-20 most recent published papers per search were also analyzed and included in the document if the paper contributed to an understanding of gene-editing in relation to one of the sustainability fields.

The analysis of the abstracts led to the following lists: 19 papers dealing with gene-editing in relation to air-pollution, transport and noise; 63 papers dealing with gene-editing in relation to biodiversity and ecosystems; 39 papers dealing with gene-editing in relation to climate change and energy; 37 papers dealing with gene-editing in relation to freshwater resources; 19 papers dealing with gene-editing in relation to marine and maritime; and 27 papers dealing with gene-editing in relation to waste and resources.

The authors in each thematic area were ranked according to times cited. It was decided to use times cited as a ranking variable, because the most-cited researchers are more likely to have a bigger impact on the development of the technology than researchers who are cited less often. Via extensive web searches the author's e-mails were found. Authors were contacted via e-mail with a request for a Skype interview. After 7 days, a reminder was sent to all scientists who had not responded yet. In total, 149 scientists were contacted via e-mail.

In total, 30 interviews were held. 21 were men, 9 were women. They were mostly affiliated to Western institutions: 14 from the European Union (Great-Britain included) and 14 from the US. But also, scientists affiliated to institutions in India (2), Shanghai (2), Australia (2) and China (1). Unfortunately, no scientists affiliated to African or South-American institutions were found. The interviews lasted on average 30 minutes.

The interviews were semi-structured, qualitative interviews. The flexibility of semi-structured interviews was beneficial to delve deeper into the topics that were discussed during the interview and were potentially interesting.

All scientists were asked the same set of questions, supplemented with questions specific to the thematic area their gene-editing research was linked to. The questions were furthermore based on the guidelines by Lucivero, Swierstra and Boenink (2011), namely to focus on the feasibility, usability and desirability of the emerging technology. See appendix 1 for the list of questions.

At the end of each interview, interviewees were asked to suggest colleagues that were worth interviewing in the context of this thesis. Through this method, 17 scientists were contacted.

c. Data analysis

All interviews were recorded on an iPhone, fully transcribed and color coded. Color coding was done in two steps. The first color coding was done according to whether the interviewee talked about the feasibility, usability and desirability of the technology. And in the second step, in more detail, the interviews were coded per thematic area, to see whether the answers pertained to the area of air pollution, biodiversity, etc. In this way, the answers of scientists could be categorized according to the environmental thematic area and be compared with each other.

d. Quality of the research

The strength of this study is the in-depth analysis of the promises and expectations of scientists working in the field of gene-editing. A limitation of the study is that stakeholders other than scientists are not included in the research process. One could think of the voice of special interest parties like Greenpeace and Friends of the Earth, but also the opinion of (livestock) farmers, policy makers and the general public. Even though this is a limitation of the study, it does not undermine the validity of the research. Scientists are an important stakeholder in the development of gene-editing technologies and play a key role in disseminating the information to the public. Researching their expectations of gene-editing in relation to ecological sustainability as defined by the six thematic areas of the European Environment Agency has never been done before and is an important first building block in forecasting the threats and opportunities of gene-editing technologies for ecological sustainability.

Table 2. List of researchers that were interviewed.

Name	Institutional Affiliation	Interview Date
Andrea Smidler	Research Assistant at the Department of Genetics at Harvard Medical School.	July 10, 2018
Antoinette Piaggio	USDA APHIS Wildlife Services.	August 30, 2018
Bjorn Heijstra*	Director of Process Validation at LanzaTech Inc.	*Interviewed via e-mail.
Dan Voytas	Director at the Center for Precision Plant Genomics at the University of Minnesota.	July 18, 2018
Dolf Weijers	Professor of Biochemistry of Plant Development at Wageningen University.	July 12, 2018
Donald Weeks	Professor of Agriculture and Natural Resources at the University of Nebraska-Lincoln.	June 27, 2018
Eduardo Blumwald	Professor at the Department of Plant Sciences at the University of California, Davis.	August 2, 2018
George Church	Professor of Genetics at Harvard Medical School.	July 19, 2018
Jason Delborne	Associate Professor in the Department of Forestry and Environmental Resources at the NC State University.	September 6, 2018
Jeantine Lunshof	Philosopher and bioethicist at the MIT Media Lab and at University Groningen.	July 2, 2018

John Hickey	Professor in Genetics and Genomics at The Roslin Institute of the University of Edinburgh.	September 3, 2018
John van der Oost	Professor at the Laboratory of Microbiology at Wageningen University.	July 5, 2018
Iannos Mougiakos	Promovendus at Wageningen University in the Department of Agrotechnology and Food Sciences.	July 2, 2018
Kailash Bansal	Director at the National Bureau of Plant Genetic Resources, New Delhi.	July 3, 2018
Kevin Doxzen	Science Communication Specialist at the Innovative Genomics Institute, UC Berkeley.	August 31, 2018
Mark Tizard	Senior Scientist at CSIRO’s Australian Animal Health Laboratory.	July 31, 2018
Marta Vasconcelos	Chief Editor of Frontiers in Plant Science and working at La Universidade Católica Portuguesa.	July 13, 2018
Nienke de Graeff	PhD student at Utrecht University researching gene-drives.	August 1, 2018
Pablo Bermejo-Álvarez	Research scientist at the Instituto de Investigación y Tecnología Agraria y Alimentaria.	September 11, 2018
Pratyoosh Shukla	Researcher at the Department of Microbiology, Maharshi Dayanand University, Rohtak.	September 4, 2018
Qi Li	PhD student at the Shanghai Institutes for Biological Sciences.	June 28, 2018
Qingzhuo Wang	PhD student at the Shanghai Institutes for Biological Sciences.	June 28, 2018
Rachel Levin	Research scientist at the University of New South Wales, Australia.	September 13, 2018

René Custers	Regulatory and responsible research manager at VIB, a life sciences research institute.	July 20, 2018
René Smulders	Plant Breeder at Wageningen University.	August 30, 2018
Robert Carlson	Author of the book Biology is Technology: The Promise, Peril, and New Business of Engineering Life.	September 7, 2018
Virginie Courtier-Orgogozo	Researcher at Institut Jacques Monod/CNRS.	Oktober 4, 2018
Wayne Powell	Principal at Scotland's Rural College.	Oktober 1, 2018
Wei Ge	Chair Professor at the Faculty of Health Sciences, University of Macau, China.	August 27, 2018
Zoë Robaey	PhD student at the Center for Ethics and Technology at Delft University.	September 12, 2018

4. Results

In the coming sections, the findings of the interviews will be discussed. The promises, visions and expectations of scientists working with gene-editing or in the field of gene-editing will be presented per thematic area as defined by European Environment Agency and embedded in current literature. The findings of the interviews are further divided into feasibility and usability claims, and desirability of the technology. To recap, the thematic areas are: air pollution, transport and noise; climate change and energy; freshwater resources; marine and maritime; biodiversity and ecosystems; and waste and resources.

a. Air pollution, transport and noise

Introduction

This thematic area covers environmental indicators relating to the emission of main air pollutants (ozone precursors like nitrogen oxide (NO_x), and acidifying substances like nitrous oxide (N_2O), passenger and freight transport demand, use of cleaner and alternative fuels, and ambient noise limit values for road traffic. Under this section, carbon dioxide and methane emissions are not considered. These will be discussed in the 'climate change and energy' section.

Seven interviewees talked about what they expected to be potential applications and risks of gene-editing in relation to air pollution, transport or noise. They highlighted applications relating to the creation of green chemicals and biofuels, and applications relating to different agricultural practices leading to less need of fertilizers. Because green chemicals and biofuels lead to less need of fossil fuels, and because fossil fuels are the major source of human-caused air pollution (Snyder, Bruulsema, Jensen & Fixen, 2009), these applications are mentioned under this environmental thematic area. Also, applications leading to less need of fertilizers are mentioned under this thematic area. These applications are mentioned in this section because of two reasons. First of all, producing fertilizers is a very energy intensive process, using about 1% of the world's total annual energy supply (Smith, 2002). Making fertilizers redundant, would indirectly lead to a lot of energy saving, and thus to a lot less air pollution. And second, fertilizers have found to be a major source of nitrous oxide (N_2O) emissions ("Nitrous Oxide Emissions", 2015), and N_2O is a major ozone-depleting substance (Ravishankara, Daniel & Portmann, 2009). Since exposure to ozone is one of the indicators used by the EEA to measure air pollution, applications leading to less use of fertilizers, leading to less ozone depletion and less exposure to ozone, are included under this section. None of the interviewees mentioned applications of gene-editing in relation to ambient noise.

Feasibility and usability

Four interviewees mentioned that genome-editing tools are indispensable in their current research when creating biofuels and green chemicals. Especially the CRISPR/cas system is used to edit microbes to produce the chemical the scientists want them to produce. A scientist explained that the advantage of CRISPR/cas compared to previous molecular biology technologies, is that with CRISPR it becomes possible to replace genes with a lot more precision. CRISPR/cas is so precise, that genes that are faulty can be replaced for genes that have a better production of the desired chemical or biofuel.

Biofuels have been heralded by some scientists as an important source of energy when trying to lower the emission of the main air pollutants (Pacala, 2004; Farrell, 2006). However, others have debated the environmental benefits of biofuels compared to fossil fuels (Scharlemann & Laurance, 2008). Especially when factoring in the emissions arising due to land use change (Plevin, Jones, Torn & Gibbs, 2010), and the N_2O emissions of the crops used for biofuels (Crutzen et al., 2016), the environmental benefits of biofuels become uncertain. However, the problem of land use change could be solved with algal biofuels, since these can be cultivated in aquaculture (Scharlemann & Laurance, 2008). And the N_2O emissions could be lowered by gene-edited crops that do not need fertilizers (Wagner, 2011).

For the transport sector specifically, biofuels could greatly reduce the sector's environmental impact. Currently, the transport sector emits 14% of the global greenhouse gas emissions, of which 6% consists of N_2O. The sector heavily relies on fossil fuels (95%) for its energy consumption, which are mainly petroleum-based fuels ("Global Greenhouse Gas Emissions Data", 2015). Biofuels, depending on the crops from which they are made, could help the sector lower its impact on air pollution (Liaquat, Kalam, Masjuki & Jayed, 2010).

Another application of gene-editing relating to air pollution is the field of plant breeding. Three plant breeders that were interviewed expected that an indirect positive effect of gene-editing on air pollution is through genetically engineered plants that don't need fertilizers. One scientist gave the example of legumes which conduct nodulation. Nodulations helps to fix nitrogen from the atmosphere and naturally fertilize the soil. Gene-editing could help plants to be more efficient at nodulation, leading to less use of fertilizers. Fertilizers are made through a process called the Haber–Bosch process, whereby atmospheric nitrogen is converted into ammonia by a reaction with hydrogen. This process is very energy-intensive, using about 3 to 5 percent of the world's natural gas production (Smith, 2002). Making fertilizers redundant, would indirectly lead to a lot of energy saving, and thus to a lot less air pollution. Besides, biological nitrogen fixation (BNF) leads to less runoff of fertilizers (Hungria et al., 2006). Fertilizer runoff has profoundly altered the nitrogen cycle and led to unwanted environmental consequences (Bohlool, Ladha, Garrity & George, 1992).

Synthetic fertilizers have facilitated an increase in the global food production (Peoples, Herridge & Ladha, 1995), but are also a cause of concern. The reactive nitrogen of fertilizers, cycles in various polluting forms. The polluting form relating to air pollution is nitric acid, which leads to acid rain (Kaiser, 2001). For the sake of completeness, it should be said that there are also polluting forms of reactive nitrogen relating to freshwater resources and biodiversity. Fertilizer runoff has led to increased nitrogen loads in freshwater resources and coastal waters (Kaiser, 2001), leading to a process known as eutrophication. Eutrophication is a process of abundant proliferation of microorganisms, especially algae. The algae cause decreased levels of oxygen, leading to vast mortality among aquatic organisms (Fields, 2004). Therefore, the environmental benefits of gene-editing to help plants fix nitrogen could also be mentioned under the sections 'freshwater resources', 'marine and maritime' and 'biodiversity and ecosystems'.

A final example of the usability of gene-editing is for the staple crop corn. 40% of the global corn production goes to feed livestock (Kaiser, 2001). One plant breeder mentioned how efforts are being done to create gene-edited corn plants that can fix nitrogen, thereby minimizing the input of fertilizer needed for the production of this staple crop.

In light of the usability of gene-editing technology, two out of seven interviewees highlighted that sustainability is often seen as a byproduct when minimizing air pollution. One scientist explained: 'We live in a society where costs are the most important part. Nobody cares if something is sustainable if it is not cost effective. That is why we create these tools to accelerate the process of establishing many microbial platforms for the production of many different chemicals, so that this becomes a cost competitive alternative to fossil fuels'. And a plant breeder mentioned that there are a lot of applications of gene-editing in plant breeding, but that those applications will only become a reality if someone sees a benefit in the application and is willing to pay for it. He stated: 'A company is anchored in economics. They need to make enough money to continue operations. The markets are well-established for food and food products. The public is increasingly demanding healthier and safer food. I think it is more difficult to market something that is going to be environmentally sustainable and have someone who is going to pay for it, than to market something that is safer and healthier'. He did see opportunities for gene-edited plants that fix nitrogen, because the economics are such that the farmer no longer would have to pay for fertilizers, thereby making the investment into these gene-edited crops profitable.

Desirability

All interviewees expected mainly positive impacts of gene-editing technologies on applications relating to air pollution. However, most interviewees agreed that using gene-editing technologies for the production of green chemicals and biofuels is only desirable when the containment of genetically modified microbes is ensured. As one scientist explained: 'In the production of biofuels, we make microbes that can resist antibiotics. In our lab, these microbes don't pose a threat. But should one of these microorganisms escape into the environment, they might exchange some of their genome with other microbes, giving antibiotic resistance to them as well. This might be dangerous'.

One scientist working on microbes for green chemicals identified a solution to the containment problem. He explained that with gene-editing, it is possible to create auxotrophic microbes. Auxotrophic microbes are microbes which lack a gene that creates a necessity for a specific nutrient that the microbes otherwise wouldn't need. By making them dependent on a nutrient that cannot be find outside the industrial complex, you ensure they do not survive in off-target areas.

None of the scientists that were interviewed highlighted unmitigable risks associated with the use of gene-editing for gene-edited plants that do not need fertilizers. One plant breeder mentioned the risk of gene flow, which happens when a trait that you edit in a crop plant moves into a natural population through crossing. He gave as an example herbicide tolerant crops, which if their trait moves into a weedy wild relative, you create an herbicide resistant weed. However, this risk can be mitigated by creating sexually incompatible crop types. This risk does not affect air pollution but is nonetheless a derivative of editing crops. We will talk about this risk more extensively in the biodiversity and ecosystems section.

I found all seven interviewees to be in favor of further developing gene-editing technologies for the production of biofuels, green chemicals or crop nodulation improvement. All scientists highlighted that gene-editing technologies are not the silver bullet that will solve all environmental problems but is a useful piece of technology that enables faster scientific discoveries and can help us in fighting some of the environmental problems we have created through our consumption pattern.

Summary

Three scientists I interviewed highlighted the importance of gene-editing for the creation of biofuels and green chemicals. Even though the environmental benefits of biofuels are contested, under the right circumstances they could provide to be a valuable alternative to the polluting fossil fuels. Four plant breeders I interviewed expected that gene-editing could play an indispensable role in creating crop types that have better nitrogen fixation, thus reducing the need for synthetic fertilizers. Given the fact that the production of synthetic fertilizers is very energy intensive, and the fertilizer run-off is a major source of air pollution, this could be a great way to minimize the environmental impact of agriculture on the quality of the air. All scientists I interviewed found gene-editing technologies to be desirable, provided that adequate biosecurity measures are taken when working on the creation of gene-edited organisms.

b. Climate change and energy

Introduction

This thematic area covers indicators relating to climate change mitigation (greenhouse gas and fluorinated gas emissions, and atmospheric greenhouse gas concentrations), climate change impacts (global and European temperature, cryosphere[2] trends for European glaciers and sea ice) and energy (share of renewable energy in final energy consumption).

Eight interviewees talked about gene-editing in relation to climate change and energy. Scientists expect both benefits and downsides to climate change, though they put much more emphasis on the benefits of gene-editing. Most of these benefits were to be found in the areas of livestock breeding and carbon sequestration.

Feasibility and usability

To begin with livestock breeding, scientists noted several applications that they expected could reduce the energy consumption and greenhouse gas emissions in livestock breeding. The breeding of livestock is responsible for 12 - 18% of global greenhouse gas emissions (Garnett, 2009; Reisinger & Clark, 2017). With the prospect that the demand for milk and meat is about to double by 2050 (FAO, 2006), lowering the amount of anthropogenic

[2] The cryosphere is that part of the earth that is either covered in water that is in solid form (ice, snow) or is frozen ground (the permafrost).

greenhouse gas emissions in the livestock sector is an important part of stopping the human contribution to the warming of the climate (Duxbury, 1994).

One scientist expected that gene-editing could half the amount of energy needed to incubate eggs by identifying the sex of an embryo in the egg. Globally, there are six billion male chicks that are culled every year from the egg production industry. Until recently it was not possible to see through the shell whether an egg contained a male or a female chick, meaning that for 22 days you needed twice the amount of incubator space, and thus twice the amount of energy, then you really needed. The scientist explained that by combing gene-editing technology with transgenic technology, it is possible to introduce a marker on the chromosome that is responsible for telling the embryo to grow into a male phenotype. In this way, it becomes possible to identify through the shell the sex of the embryo and safe half the number of incubators and energy.

Another application of gene-editing was mentioned by a livestock breeder, who explained that with gene-editing it becomes possible to identify cows that produce fewer methane. By tweaking genes, the livestock breeder explained that you can shape which bacteria live in a cow's gut and this in turn impacts the amount of gases emitted by the cow. Since the production of livestock contributes about 20 - 34% of the global production of methane (IPCC, 2000), and methane contributes about 20% of the estimated anthropogenic radiative forcing (Johnson, Franzluebbers, Weyers & Reicosky, 2007), breeding cows that emit a lower amount of methane could be a climate change mitigation effort of the livestock industry. But is it desirable that this technology can be used in a business that is inherently unsustainable compared to plant-based diets?

One scientist mentioned the expectation to decrease the emission of greenhouse gasses by repopulating the area with herbivores to stop the release of carbon in the tundra.

This speculative project has garnered a lot of media attention, because of the potential impact it could have. There are about 1400 gigatons of carbon in the tundra, quite a bit of which is methane, which is 30 to 80 times more potent per molecule than carbon dioxide. To put this number into perspective: globally humans consume about 9 gigatons of carbon per year from all sources combined. If nothing is done to stop the soil temperature from rising, the 1400 gigatons are at risk of being released into the atmosphere. Due to the hunting of herbivores by humans in the tundra, the landscape switched from grass to trees. The trees now provide an insulating layer retaining the summer heat on the ground, so the ground doesn't cool in winter as much as it should. The scientist and his team are researching the possibility to create cold-resistant elephants, that could take down the trees and punch down the snow in wintertime, to make sure the soil does not warm too much in the summer. But is such an application that radically impacts the balance of the local ecosystems desirable?

Desirability

None of the scientists foresaw any risks of gene-editing relating to climate change and energy. However, 4 out of 8 scientists highlighted there are risks we might not know about yet. Nonetheless, all scientists were in favor of further developing the technology. One scientist explained we should further develop the technology, because there are risks of not doing things too. In the case of the melting of the permafrost, there is a risk of the release of 1400 gigatons of greenhouse gasses. The status quo already brings risk with it. There is no risk-free world. The question of the measurement of risk is something that three other scientists highlighted as well. Their opinions came down to the notion that for a scientist, risk is measurable. And even though there are risks we might now know about, we can up to a certain degree anticipate on possible side effects of applications of the technology. The question then becomes: how do we decide which risks are acceptable? In the case of the repopulation of the tundra with herbivores, there is a risk of bringing about a disequilibrium in the local ecosystem by introducing new species (a risk that does not directly relate to climate change but is an indirect result of trying to stop the release of carbon into the air). Which risk are we more willing to take: the melting of the permafrost or potentially bringing about a disequilibrium in the local ecosystem?

Another question that can be asked when assessing the applications of gene-editing to combat climate change and reduce the energy consumption is which economic sectors should benefit from this technology. Should the technology be used to help an unsustainable business like the poultry industry become more efficient? Should the technology be used to reduce the methane emission of cows, when we know that beef is among the most polluting forms of food when compared to plant-based diets? (Eshel, Shepon, Noor & Milo, 2016). Or should we encourage applications that reduce the environmental impact of these industries, even though they may be unsustainable compared to alternative sources of food?

Summary

Four scientists that were interviewed highlighted several applications that they expected could potentially reduce the energy consumption and greenhouse gas emissions in livestock breeding. One scientist expected that gene-editing could half the amount of energy needed to incubate eggs by identifying the sex of an embryo in the egg. Another application of gene-editing livestock breeding was mentioned by a livestock breeder, who explained that with gene-editing it becomes possible to identify cows that produce fewer methane. The expectation that garnered most media attention was that gene-editing could facilitate the repopulation of the tundra with gene-edited herbivores, to stop the release of carbon from the melting permafrost. None of the scientists mentioned any risks of gene-editing relating to climate change and energy. However, 4 out of 8 scientists highlighted there are risks we might not know about yet. Nonetheless, all scientists were in favor of further developing the technology. Questions about the desirability of the technology can be asked in regard to applications for an unsustainable industry like the meat industry.

c. Freshwater resources

Introduction

This thematic area covers environmental indicators relating to the use of freshwater resources, the quality of freshwater resources, and pressures on freshwater resources deriving from the agricultural use of nitrogen and pesticides.

Eight scientists talked about potential opportunities and threats of gene-editing relating to freshwater resources. The most prominent expectation among scientists was that gene-editing would allow for the creation of drought resistant crops, and more in general crops with a more efficient water to harvestable mass ratio, thereby decreasing the agricultural use of freshwater resources. Scientists also highlighted that gene-editing might indirectly decrease the use of freshwater resources by increasing the feed efficiency of cattle and poultry. No scientists that were interviewed saw any direct risks for freshwater resources by using gene-editing in crops and animals. However, two scientists who gave an example of gene-edited drought resistant crops expressed their concern that using gene-editing in agriculture encourages a reductionist view on biology.

Feasibility and usability

The most prominent expectation among the interviewed scientists is that gene-editing will facilitate the creation of more water efficient crops. Five plant breeders mentioned efforts to create crops that are more resilient to drought. Given the forecasts that drought will become more erratic as the climate warms, these types of crops will be very useful in the future to ensure that agriculture is possible in semi-arid areas (Jackson, Claude & Godfrey, 2018). In this way, the usage efficiency of the available freshwater resources for agriculture can be optimized.

Scientists expect gene-editing can reduce the pollution of water by creating pest resistant crops, thereby making the need for pesticides redundant. Every year, about $38 billion are spent on pesticides (Pan-Germany, 2012). Ideally, the pesticide should only reach the targeted organism, be biodegradable and environmentally friendly (Rossell et al., 2008). However, studies have shown that only 0.1% of the pesticides reaches the targeted organisms, and the remaining volumes pollute the surrounding environment, also the aquatic environment (Carriger et al., 2006). Especially in the treatment of wastewater, it has been found difficult to eliminate the pesticides from the water (Köck-Schulmeyer et al., 2013).

Given these big impacts of pesticides on the water quality, creating pest resistant crops could potentially mitigate a lot of water pollution. A plant breeder I interviewed explained that gene-editing could help us to breed those pest resistant crops faster compared to traditional breeding methods. He highlighted that the faster we can breed these new varieties, the earlier we can get rid of all the chemicals we use in agriculture. He gave an example of the Golden Delicious apple, which does not have disease resistance and has to be sprayed every week for twenty weeks to make sure the apples are not affected by a disease. He explained that with gene-editing, we could modify a single gene in this apple variety to add disease resistance and in that way make spraying pesticides redundant.

Scientists expected similar opportunities with regards to substituting synthetic fertilizers by gene-edited plants that use less nitrogen and phosphorus inputs or fixate their own nitrogen more efficiently. Fertilizer run-off is one of the main sources of freshwater pollution, leading to eutrophication (Kaiser, 2001). Creating plants that do not need synthetic fertilizers could therefore be a big opportunity to mitigate this source of pollution. One scientist gave the example of the promise of gene-edited legumes, which could potentially conduct nodulation more efficiently to lower the use of fertilizers.

One animal breeder mentioned an application of gene-editing that in his opinion could potentially improve the efficiency of freshwater usage. The application is related to the cattle and poultry industry. The scientist expected that because gene-editing allows for faster breeding methods, it becomes possible to increase the feed efficiency of cattle quicker, thus needing less water for growing crops per kilogram of meat. According to the animal, traditional breeding methods have accomplished a 79% improvement in feed efficiency in the poultry industry in the past 50 years. He explained now that breeders have access to genome editing, they can potentially double the rate at which feed efficiency is increased.

Since about 3 kilograms of feed are needed for each kilogram of meat (Hansen & Gale, 2014) and 15.415 liters of water (Heffernan, 2017), feeding a growing population of livestock animals will be a challenge given the limited freshwater resources we have on our planet. With an 80% probability that the world population will increase to between 9.6 and 12.3 billion in 2100 (Gerland et al., 2014) and surging meat demand in countries like China due to rising living standards and availability of a wider variety of foods from supermarkets (Hansen & Gale, 2014), increasing the feed efficiency of animals will be an integral part of the solutions needed to meet the growing meat demand while at the same time dealing with the limited freshwater resources we have at our disposal.

Desirability

Knowing that the production of one kilogram of beef costs 15.415 liters of water, also raises questions about the desirability of using gene-editing to improve feed efficiency in livestock. The World Economic Forum has listed water scarcity as the largest global risk in terms of potential impact (World Economic Forum, 2015). It is estimated that two thirds of the world population deal with severe water scarcity at least one month of the year, and half a billion people all year round (Mekonnen & Hoekstra, 2016). Should we not stop the production of meat given the plant-based food alternatives we have that require much less water? (Eshel, Shepon, Noor & Milo, 2016).

The scientists that were interviewed did not highlight any risks for freshwater resources by using gene-editing to create more water efficient crops or more feed efficient animals.

Summary

The most prominent expectation among the interviewed scientists is that gene-editing will facilitate the creation of more water efficient crops. Scientists expect gene-editing can reduce the pollution of water by creating pest resistant crops, thereby making the need for pesticides redundant. Given the big impacts of pesticides on the water quality, creating pest resistant crops could potentially mitigate a lot of water pollution. Scientists expected similar opportunities with regards to substituting synthetic fertilizers by gene-edited plants that use less nitrogen and phosphorus inputs or fixate their own nitrogen more efficiently. One scientist expected that because gene-editing allows for faster breeding methods, it becomes possible to increase the feed efficiency of cattle quicker, thus needing less water for growing crops per kilogram of meat.

The scientists that were interviewed did not highlight any risks for freshwater resources by using gene-editing to create more water efficient crops or more feed efficient animals. Even though efforts to use gene-editing to improve feed efficiency in livestock and thereby indirectly reduce the water usage can be appreciated, questions about the desirability of such applications are raised given the plant-based diet alternatives we have for meat that require far less amounts of water to grow and produce.

d. Marine and maritime

Introduction

This thematic area covers indicators relating to the water quality of transitional, coastal and marine water; the status of marine fish stocks; the sea surface temperature and the global and European sea level rise.

Five scientists talked about the potential opportunities and threats of gene-editing they expect for coastal and marine waters, and marine life. Scientists expected that the biggest application in terms of possible impact was the adaptation of bleaching corals to rising sea temperatures. Due to the difficulty of finding researchers involved in gene-editing for marine life purposes, I found only scattered expectations in relation to fish and other marine organisms. This may indicate that compared to terrestrial biodiversity, far less research is being done on fish and other marine life.

Feasibility and usability

Two scientists highlighted how they expected that gene-editing could potentially help bleaching corals cope with the rapid sea temperature rise. Coral bleaching is a stress response to extended warmer periods (De'ath, Lough, & Fabricius 2009) that results in the loss of symbiotic algae and their pigments (Brown, 1997). Symbiotic algae are little algae that photosynthesize to feed the coral. In return, the coral provides the algae with nutrients and a place to live. This mechanism between coral and symbiotic algae is always adaptable environmental changes: the coral can at any time spit out the symbiotic algae and find a partner that is better suited for the current climate that it is living in. However, due to the increased concentrations of greenhouse gases in the atmosphere, sea temperature is rising faster than normal (Eakin et al., 2009), and the algae have no time to evolve with the changing climate. When the corals spit out the symbiotic algae, there is no better partner living in the water column. Because of that, the corals do not have any food source, and ultimately die if they do not find a new genetic variant of symbiotic algae that is well-adapted to the current environment to form a partnership with.

One scientist explained that she and her team are trying to apply gene-editing technologies to reduce coral bleaching by genetically engineering the microalgae found in corals. The idea is to assist the evolution of microalgae by finding a gene with tolerance to heat that is already existing inside of the symbiotic organism and give it extra copies of that gene. She explained that gene-editing plays a crucial role in this process, because it is not about trying to introduce new genes from a foreign organism but finding a gene that is already existing inside the microalgae and multiply it. In this way, the corals can form a partnership with a genetic variant of the symbiotic algae that is well-adapted to the increased water temperatures.

Coral bleaching has many negative consequences for the environment. It poses a significant threat to coral reef ecosystems, with declining numbers in the population of reef fishes like butterflyfishes, damselfishes and gobies of up to 60% as a consequence (Pratchett, Hoey, Wilson, Messmer & Graham, 2011). Furthermore, the death of coral reefs leads to a reduction in the diversity of fish species (Wilson et al. 2006). One of the major coral ecosystems affected by rising sea temperature is the Great Barrier Reef. It remains uncertain to what extent corals may adapt to the changing aquatic environment (Mumby & Van Woesik, 2014), so assisted evolution through gene-editing may provide a valuable solution to helping the corals survive in higher water temperatures.

One scientist highlighted how gene-editing helps to do research on the rainbow trout. The rainbow trout is a species that originates from the Northwest coast of North America and is of major importance for aquaculture and wild stock fisheries (Bobe et al., 2016). The interviewed scientist and his team produce knock-out and knock-in models of the trout to study fundamental questions of biology. Since the gene-edited trout are not allowed for human consumption, research is being done on the reproduction and growth of the fish. The scientist explained that with the technology as it is right now, it could be used to generate an abundance of different traits in trout. Unfortunately, he did not expand on what these traits could be.

Desirability

Three scientists that I interviewed mentioned some potentially serious risks when using gene-editing in marine organisms. One point of concern expressed by the scientists is that by assisting the evolution of symbiotic algae, you may introduce one variant that can handle heat very well but outcompetes all the other genetic variants that exist and thus destroys the genetic variation. This makes a coral reef vulnerable to new climate changes, as the current dominant variation might not be suited to cope with the new environmental conditions, and there are no other genetic variants to choose from to adapt to the changed circumstances.

One scientist expected that a way to mitigate the risk of one type of symbiotic algae dominating all other variants would be by creating different genetic variants instead of one that is overly robust. However, she emphasized that this is an unknown area, since scientists right now are in the beginning stages of being able to create such a variant, let alone release it and see what it does to competing organisms.

Two scientists expressed their concerns over the difficulty of containing gene-edited fish and the possible negative effects an escape could have on native fish populations. Even though scientists highlighted that raising the gene-edited fish inland in contained tanks could lessen the chances the animals escaped into the wild, deliberate attempts of people to release these animals into the wild is a risk that is hard to mitigate.

This point of concern was also heard by environmental groups in 2015, when the Food and Drug Administration (FDA) of the United States approved a genetically engineered salmon for consumption (Pollack, 2015, November 19). The AquAdvantage salmon is an Atlantic Salmon that was engineered in such a way that it could grow to market-size twice as fast as a non-engineered salmon (Pollack, 2015, November 19). An escape into open waters could mean that the genetically engineered salmon would disrupt ecosystem balances and dominate all other salmon types.

Summary

Two scientists highlighted how they expected that gene-editing could potentially help bleaching corals cope with the rapid sea temperature rise by genetically engineering the microalgae found in corals. One scientist highlighted how gene-editing helps do research on the rainbow trout.

Three scientists that I interviewed mentioned some potentially serious risks when using gene-editing in marine organisms. One point of concern expressed by the scientists is that by assisting the evolution of symbiotic algae, you may introduce one variant that can handle heat very well but outcompetes all the other genetic variants that exist and thus destroys the genetic variation. Two scientists expressed their concerns over the difficulty of containing gene-edited fish and the possible effects an escape could have on native fish populations.

The difficulty of finding scientists working on gene-editing in relation to fish and other marine organisms may indicate that compared to terrestrial biodiversity, less research is being done on fish and other marine organisms in relation to gene-editing.

e. Biodiversity and ecosystems

Introduction

This thematic area covers environmental indicators relating to the abundance and distribution of species, the loss and degradation of ecosystems, and the status of forests.

What threats and opportunities does gene-editing technology offer for the biodiversity and ecosystems on our planet? Thirteen scientists shared their insights on this question. The scientists mentioned both potential positive and negative impacts of gene-editing on biodiversity and ecosystems. They highlighted applications relating to the eradication of invasive species and malaria mosquitoes, the de-extinction of extinct species like the American chestnut tree, and the breeding of animals. Scientists expressed their concern relating to the containment difficulties of gene-driven organisms, the collapse of ecosystems due to the removal of a key stone species and the negative influence market forces focused on profits could have on the possible utilization of the technology for biodiversity and ecosystems.

Feasibility and usability

Three scientists that I interviewed were working with gene-editing to wipe out an invasive species from a certain area by letting a gene-drive run through the targeted population. One scientist illustrated that a possible application of a gene-drive is to eradicate mice and rats on islands where they are invasive. Invasive rodents are one of the major threats to islands biodiversity and are responsible for a great number of extinctions and ecosystem changes (Howald et al., 2007; Angel, Wanless & Cooper, 2008). There have been recent studies that show that when you remove invasive mice and rats from islands, a lot of native plants and animals return (Giller, 2018). Currently, the only effective way wildlife conservationists combat the rodents is by putting toxicants in the landscape (Leitschuh et al., 2017). Though effective, this method is very costly and are not species-specific: a lot of other animals also eat from the bait, making the off-target effects big (Leitschuh et al., 2017). Gene-drives offer a solution to this problem. By creating a gene-drive that makes one-sex offspring, theoretically the invasive population should vanish after a few generations without affecting other animals.

Another application of gene-drive technology mentioned by scientists is to potentially eliminate malaria mosquitoes to preserve avian fauna in Hawaii. In the 1840's, a mosquito species that transmits avian malaria was imported into Hawaii that started to wipe out the native bird species (Warner, 1968; Atkinson, Dusek, Woods & Iko, 2000). By introducing a one-sex gene-drive into the mosquito species, the invasive mosquito species could be eliminated. The need for this application is becoming more and more pressing due to the warming climate: now, mosquitoes cannot survive in the cold at the top of the mountains, while the birds can live about a mile above where the mosquito range is. Due to climate change, the mosquito range is climbing up the mountains, invading the habitat of the birds (Harvell, 2002). The release of a gene-drive in mosquitoes could therefore potentially preserve a lot of avian fauna on Hawaii.

It should be emphasized that the release of such a gene-edited mosquito is likely to happen in the near future. The scientists I interviewed emphasized that the gene-drives developed in the laboratory do not function as well as they should, and that the biosecurity regulations around the release of gene-edited organisms into the environment are not fully in place yet. Nonetheless, advancements in the development of gene-drives are being made, and researchers keep exploring the possibilities of the release of a gene-drive in among other mosquitoes.

A final application of a gene-drive that was mentioned by the interviewees was the release of a gene-drive in the European carp in Australian waterways. Carp were introduced by Europeans about a century ago and are now causing significant damage and erosion to the native fish and the Australian aquatic ecosystems (Pinto et al., 2005). One scientist mentioned that he and his team are researching the possibility of introducing a gene-drive into the carp population so that the population collapses within a couple of generations. Even though eliminating the invasive carp does not automatically mean that the indigenous varieties will once again flourish, a further spread of carp in the Australian aquatic environment would mean that more native fish populations will be suppressed, bringing about disruptions to habitats and ecosystem functions (Gozlan, Britton, Cowx & Copp, 2010). Since all Australian surface waters appear to be climatically suitable for carp (Koehn, 2004), there is a strong need for effective methods to control the carp population.

Scientists also mentioned ways gene-editing could be used to restore biodiversity, by the so-called de-extinction of species. One scientist gave the example of bringing the American chestnut tree back into the landscape. The chestnut trees were once a major component of the American hardwood forests but were wiped out by the chestnut blight, a fungal disease, in the beginning of the 20th century (Anagnostakis, 1987). Only a couple of dying trees remained (Hepting, 1974). Besides being of great economic importance to the rural areas in the United States due to the great value of the hardwood, chestnuts were also important because they made up an important part of the diet of squirrels, wild turkeys and other wildlife (Hepting, 1974). The scientist I interviewed highlighted the current efforts using a wheat-gene to create a blight-resistant tree. The hope is that one day the American chestnut tree will repopulate the American Eastern forests again (Specter, 2016).

Through interviews with animal breeders, it became clear that gene-editing offers possibilities to breed livestock animals faster. Globally, there are about 40 species of animals that we use as domestic livestock (Barker, 1999). Within these species, there are about 4500 breeds that together constitute the global animal genetic resources. Due to inefficient utilization, more than 30% of those breeds are at risk of extinction (Barker, 1999). Animals breeders I interviewed disagreed about whether gene-editing helps to preserve animal genetic diversity or threatens it.

One animal breeder explained that gene-editing allows for a more efficient way of increasing the frequency of favorable alleles in livestock populations over time. Traditionally, this was done over selective breeding, and selective breeding has been very successful. But the scientist explained that it is not as efficient as a technology like genome editing could be. The reason for that is that genome editing is able to get individual alleles and drive them to fixation for the favorable allele very quickly, in one or two generations. He elaborated that gene-editing does this much more efficiently in terms of the utilization of genetic resources than selective breeding, because these individual alleles are driven to fixation without any impact on the surrounding genome. In this way, breeders can better preserve and utilize genetic diversity.

Another animal breeder countered this view by highlighting that a risk of CRISPR is that it may actually reduce biodiversity. He explained that by improving genetic selection, you may end up using only very few breeds, thereby reducing the genetic diversity. He mentioned that this risk was already there with traditional breeding methods but that it has only become bigger now that the speed and efficiency of breeding have increased due to genome editing.
No studies on the impact of gene-editing on the genetic diversity of livestock animals were found, not making it possible to back up the visions of the animal breeders with scientific data.

Desirability

All scientists that talked about gene-editing in relation to biodiversity and ecosystems were in favor of further developing the technology, although many emphasized we should proceed with great caution, especially in the case of gene-drives.

Scientists seem to make a big difference between the desirability of gene-editing in crops and placing gene-drives in animals. For gene-editing in crops, scientists do not see any major risks for biodiversity. The biggest problem highlighted by a scientist with regards to gene-editing in plants was the risk of gene flow. The scientist explained that a trait like herbicide tolerance could move into a weedy wild relative, creating herbicide resistant weeds and thereby upsetting the ecosystem balance. But he emphasized it is possible to mitigate this risk by creating synthetic species which are sexually incompatible with weedy relatives.

In contrast to gene-editing in plants, scientists do see risks in releasing a gene-drive into a wild animal or insect population. The one issue almost all scientists highlighted was the problem of containment: how do you make sure that a gene-drive does not reach an untargeted population? There are efforts being done to design gene-drives that are geographically bound, the so-called Daisy-chain gene drives (Noble et al., 2016), but nonetheless concerns over the release of a gene-drive remain.

One of those concerns is that a local ecosystem might collapse once a key species population is eliminated through a gene-drive. This concern was especially mentioned by wildlife conservationists, who gave the example of a gene-edited mouse getting off an island and mating with mouse populations in other areas where they are an important part of the ecosystem. But the concern of an ecosystem collapse was not shared to the same extent by scientists working on gene-drives in mosquitoes, who highlighted that due to the high number of mosquito species (more than 3200 (Harbach & Kitching, 1998), it is unlikely that the ecosystem balance will be greatly disturbed if one mosquito type carrying malaria disappears. So, scientists see risks for the release of gene-driven animals, but not to the same extent for different species.

In the case of the release of a gene-drive in carp, a scientist mentioned the risk that somebody with bad intentions might release a gene-driven all-male carp in a waterway where carp are an important part of the ecosystem. The scientist proposed an alternative to an all-male gene-drive that might be more desirable. He explained that a gene-drive that is responsible for the carp’s response to a toxin that is used to clear them out in waterways might be a safer bet. The toxin is called rotenone and is currently put in the water to kill everything, including native fish. The rationale behind this is that over time the native fish will come back, and the carp hopefully will not. If a gene-drive could affect the system in carp that makes them extremely sensitive to levels of rotenone, levels of rotenone that would not affect native fish, it would be possible to let a gene-drive run through the carp population after a while hit the waterways with low levels of rotenone. In this way, the risk is mitigated that someone deliberately takes a carp and puts it somewhere where it should not be, because in order to be successful, they also have to use rotenone as a follow up. That is a two-stage process, which would make a bioterrorist action almost worthless. Because if you are going to put a small amount of rotenone in the water, why not put a lot and destroy all the fish in the waterways?

One might say that in the ideal situation no toxin at all should be put in the waterways. Studies have shown that even though rotenone is relatively harmless to plants and mammals, it is extremely toxic for insects and invertebrates, at levels as low as 0.5- to 0.6-mg/L (Chandler & Marking, 1982). This would mean that only if the gene-drive can make carp sensitive to extremely low levels of rotenone this eradication method would not have detrimental environmental effects. There are alternatives to manage carp populations. For example, the Williams cage, which is a simple device that exploits the jumping behaviour of non-native carp to selectively remove them from the waters (Stuart, Williams, McKenzie & Holt, 2006).

A couple of scientists I interviewed highlighted the concerns they have about the intentions of the user when using this technology, which could pose a threat to the biodiversity on our planet. One scientist highlighted the possibility that someone in power would decide to utilize ecological engineering methods to remove animals from woods, so they can cut down the trees and sell the wood. This is a risk that would impact vast ecosystems. A similar line of reasoning was mentioned by three other scientists who shared their concerns about the market driving innovation choices. One of them expected that even though we could be really excited about the potential of gene-editing in terms of transformation of plants and new traits, it is likely that only those applications will be made that benefit large corporations. The scientist drew a parallel with the promises made at the advent of biotechnology, and that all we got was BT cereal crops and herbicide tolerant crops. This utilization of the technology to the benefit of large corporations made mono-cultures even more profitable, thereby greatly reducing the biodiversity on vast plots of land (Perfecto et al., 1997). The scientist expressed his concern that we might see the same development around gene-editing technologies if the technology is only funded and developed by parties who are driven by profits. If on the other hand there are more ecological and social values driving innovation, the scientist expected that gene-editing might become a real blessing.

The concern of scientists about the values driving innovation asks for more than an analysis of the effects profit-driven values can have on biodiversity. It asks a fundamental question about the system we live in: Whose benefits are considered when dreaming up possible applications of gene-editing technologies? Can this technology be used for the good of all mankind in a capitalistic system which is driven by profits? Or will this technology only profit the rich if we leave the choices of application of the technology to the market?

Summary

Three scientists that I interviewed mentioned the possibilities that gene-editing potentially offers to wipe out an invasive species from a certain area by letting a gene-drive run through the targeted population: in rodents on islands, in mosquitoes on Hawaii and in carp in Australia. Scientists also mentioned ways gene-editing could be used to de-extinct species. One scientist gave the example of bringing the American chestnut tree back into the landscape by using a wheat-gene to create a blight-resistant tree. Through interviews with animal breeders, it became clear that gene-editing offers possibilities to breed livestock animals faster. The animal breeders I interviewed disagreed about whether gene-editing helps to preserve animal genetic diversity or threatens it.

Scientists seem to make a big difference between the desirability of gene-editing in crops and placing gene-drives in animals. For gene-editing in crops, scientists do not see any major risks for biodiversity. However, scientists do see risks for the release of gene-driven animals, but not to the same extent for different species: in mosquitoes the risks seem to be lower than in rodents and carp. Scientists expressed their concern about the values that drive innovation, which could potentially impact ecosystems and biodiversity in a negative way. This concern poses a fundamental question about the system we live in: Whose benefits are considered when dreaming up possible applications of gene-editing technologies?

f. Waste and resources

Introduction

This thematic area covers indicators relating to waste generation, waste recycling, energy efficiency and the decoupling of resource use from environmental pressures and impacts. This last indicator relates to the reduction of material consumption, essentially 'doing more with less' ("Resource efficiency", 2015, February 18).

Seven interviewees talked about the threats and opportunities they expect of gene-editing in relation to waste and resources. The most prominent expectation among the interviewed scientists was that gene-editing can reduce the chemical waste of farmers, though this expectation was contested by one scientist. Another expectation of scientists was that gene-editing can help decrease the nutrient input needed to feed livestock animals. A third expectation mentioned by scientists was that gene-editing offers possibilities to lengthen the shelf life of perishable products, thereby potentially decreasing the waste generations of for example supermarkets and households.

Feasibility and usability

Five plant breeders highlighted that they expect that gene-editing offers possibilities to reduce the chemical input needed to grow crops, thereby reducing the chemical waste of farmers. One scientist gave the example of Bt Cotton, a genetically modified variant of cotton with strands of the Bacillus thuringiensis (Bt) bacterium inserted into its genome. Bt cotton is resistant to several major insect pests (Shelton et al, 2002; Hutchison et al., 2010) and reduces the farmer's need for spraying insecticides (Bale, van Lenteren & Bigler, 2008; Gatehouse, Ferry, Edwards & Bell, 2011). It was first commercialized in the US in the mid 1990's but is now widely adopted throughout the world. Studies show that Bt cotton has a lower environmental impact compared to conventional cotton due to lower insecticide use (Knox, Constable, Pyke & Gupta, 2006). Given the huge area's that are covered with cotton – in northern China alone 2.6×10^6 ha of cotton is cultivated annually by more than 10 million small-scale farmers (Lu, Wu, Jiang, Guo & Desneux, 2012) – Bt cotton has greatly reduced the chemical waste of agriculture (Abedullah, Kouser & Qaim, 2014).

Two animal breeders that were interviewed illustrated how gene-editing offers possibilities to create animals that do not require certain nutrients as supplements, thereby reducing the resource use of growing livestock. One animal breeder gave the example of the Enviropig. The Enviropig is a pig breed that can digest phytate in plant seeds, which is an enzyme that catalyzes the separation of phytic acid, an organic form of phosphorus (Humer, Schwarz & Schedle, 2014). In this way, farmers no longer have to supplement pigs with phosphorus, thereby decreasing the nutrient input needed to feed livestock animals.

Phosphorus is an essential nutrient to grow livestock animals, but the phosphorus reserves on our planet are finite (Humer, Schwarz & Schedle, 2014). Most phosphorus is produced from a precious phosphate-rock through a very energy intensive process (Jegannathan and Nielsen, 2012). When the diet of pigs is supplemented with phosphorus, 50 to 80% of it is excreted through fecal material (Kornegay and Harper, 1997), which is then spread over land. Due to high phosphorus concentrations in manure, this practice leads to nutrient over-enrichment, putting a lot of pressure on soil and water quality (Correll, 1998; Smith et al., 1999).

Because Enviropigs are able to digest all the phosphorus in the cereals and soybeans they are fed, their fecal material contains up to 60% less phosphorus than pigs fed the same diet without supplemental phosphate (Forsberg et al., 2003). Computer simulations estimated that 33% less land would be needed to spread the manure from the Enviropig compared to conventional pig breeds (Forsberg et al., 2003). Using gene-editing to allow pigs to digest phytase could thus potentially decouple a part of the resource use needed to grow pigs from its environmental pressures and impacts, in this case the demand for phosphorus and the pressure on water and soil quality.

One scientist highlighted the possibilities gene-editing offers to lengthen the shelf life of fruits and vegetables, thereby reducing the waste generation of for example supermarkets and households. Globally, around 1.3 billion tons of food are wasted every year (FAO, 2013). Most of this waste comes from fruits and vegetables: a study done amongst six Swedish supermarkets showed that the fruit and vegetable department accounts for 85% of the wasted food (Scholz, Eriksson & Strid, 2015). The EU has set concrete targets to reduce the amount of food waste. By 2020, the amount of edible food waste should be halved (EC, 2011). One scientist explained that gene-editing could contribute to this goal, by selectively breeding fruits and vegetables to reduce the rate at which they decay on supermarket shelves. He illustrated that gene-editing is a helpful tool for this, because it allows to increase the frequency of alleles that lengthen shelf life.

Desirability

Most scientists agreed that gene-editing is a valuable tool when improving crops and animals. Especially when looking at the applications to reduce the chemical and nutrient input needed to grow crops and animals, scientists expected mostly environmental benefits from using the technology. Six out of seven interviewees expected that gene-editing would decrease the waste generation in various sectors.

However, the vision that gene-editing may potentially reduce the chemical input needed to grow crops was not shared by all scientists that I interviewed. One scientist actually expected that gene-edited crops would lead to an increase in the use of chemicals. He illustrated his point by mentioning the gene-edited crops for herbicide resistance have led to incredible resistance by weeds to the herbicides that have been used (mainly glyphosate) and that as a result of this, agrochemical companies have moved to Dicamba, a much more toxic herbicide. It is surprising that this negative effect of gene-edited crops was only mentioned by one scientist.

Summary

Five plant breeders highlighted that they expect that gene-editing offers possibilities to reduce the chemical input needed to grow crops, thereby reducing the chemical waste of farmers. However, this view was contested by one scientist, who expected that gene-edited crops would lead to an increase of chemical use in agriculture. Two animal breeders that were interviewed mentioned how gene-editing offers possibilities to create animals that do not require certain nutrients as supplements, thereby reducing the resource use of growing livestock. This application was illustrated with the Enviropig, a pig breed that can digest phytate much more efficiently and thus does not need phosphorus supplement in its diet. One scientist highlighted the possibilities gene-editing offers to lengthen the shelf life of fruits and vegetables, thereby reducing the waste generation of for example supermarkets and households. Most scientists agreed that gene-editing is a valuable tool when improving crops and animals.

5. Conclusion

There had been no previous studies on the scientists' expectations of gene-editing technologies in relation to ecological sustainability. This thesis aimed to contribute to this understanding. The research question was: what do scientists expect to be the main potential threats and opportunities of gene-editing technologies for ecological sustainability?

In order to answer the research question, 30 scientists with expertise in both gene-editing and ecological sustainability were interviewed. The findings were grouped per thematic area, as categorized by the European Environment Agency in their Core Set of Indicators.

Overall, scientists expect both threats and opportunities for gene-editing in relation to ecological sustainability. For the thematic area of air pollution, transport and noise, scientists highlighted applications relating to the creation of green chemicals and biofuels, and applications relating to different agricultural practices leading to less need of fertilizers. One of the main expected threats was an escape of genetically modified microbes, but scientists explained that the impact of this risk could be decreased by the creation of auxotrophic microbes.

For the thematic area of climate change and energy, scientists expected both benefits and downsides to climate change, though they put much more emphasis on the benefits of gene-editing. Most of these benefits were to be found in applications that lower the emission of livestock animals. None of the scientists foresaw any risks of gene-editing relating to climate change and energy, but four scientists highlighted there are risks we might not know about yet and emphasized we should proceed with caution when investigating the possible applications of the technique.

For the thematic area of freshwater resources, the most prominent expectation found among scientists was that gene-editing would allow for the creation of drought resistant crops, and more in general crops with a more efficient water to harvestable mass ratio, thereby decreasing the agricultural use of freshwater resources. The scientists that were interviewed did not highlight any risks for freshwater resources by using gene-editing to create more water efficient crops or more feed efficient animals.

For the thematic area marine and maritime, scientists expected that the biggest application of gene-editing in terms of possible impact was to assist bleaching corals to adapt to rising sea temperatures. Scientists shared their concerns that gene-editing in marine organisms might destroy the balance in ecosystems if the edited organisms would become dominant.

For the thematic area of biodiversity and ecosystems, scientists expected both potential positive and negative impacts of gene-editing on biodiversity and ecosystems. They highlighted applications relating to the eradication of invasive species and malaria mosquitoes, the de-extinction of extinct species like the American chestnut tree and creating more genetic diversity among breeds of animals. Scientists seemed to make a big difference between the desirability of gene-editing in crops and placing gene-drives in animals. In contrast to gene-editing in plants, scientists did mention risks in releasing a gene-drive into a wild animal or insect population.

For the thematic area of waste and resources, the most prominent expectation among the interviewed scientists was that gene-editing could reduce the chemical waste of farmers. This view was contested by one scientist, who expected the opposite to happen due to herbicide resistant weeds.

Future research could be done on the expectations of other stakeholders in relation to gene-editing and ecological sustainability. For example, policy makers, special interest groups and the general public, but also farmers and industry owners. The success or failure of a technology is dependent upon many more factors than only scientists, so researching the expectations of other stakeholders could improve the quality of the forecast of the possible impact of gene-editing technologies on ecological sustainability.

6. Acknowledgements

I would like to thank all the interviewees for their time and collaboration. I would also like to thank my supervisor Koen Beumer, whose guidance and feedback were invaluable in writing this thesis. Praise be to God for giving me the gift of life.

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8. Appendix 1

Interview questions

INTRO
How does your work relate to gene-editing?

IMPACTS
What do you expect of gene-editing? What do you think is the impact on ecological sustainability?
What do you think are the positive impacts of gene-editing on ecological sustainability?
And what do you think are the negative impacts?
Why do you think this will be positive/negative impacts?
How do they come about?
Could you give an example of a positive/negative impact?

CIRCUMSTANCES
Do the impacts occur under all circumstances? Or are there specific circumstances needed to get the positive/negative impacts?
What needs to be done to create these circumstances?
How could we prevent the negative impacts?
How will the risks and benefits be distributed?
Who should be doing what to achieve this?
What are important barriers?

RISKS
What level of risk should we accept?
Who should decide what level or risk is acceptable?
What other impacts can we anticipate?
How might these change in the future?
What don’t we know about?
What might we never know about?
Overall, is gene-editing a blessing or a curse for humanity?
Why?

QUESTION SPECIFIC TO EPI AND PAPER PUBLISHED BY THE SCIENTIST
To what extent do gene-drives pose a risk to biodiversity?
What benefits could gene-editing have for the animal industry and animal welfare?
What benefits could gene-editing have for marine life?
Who should decide the boundaries of gene-editing technologies?
What role does the government play in regulating this technology?

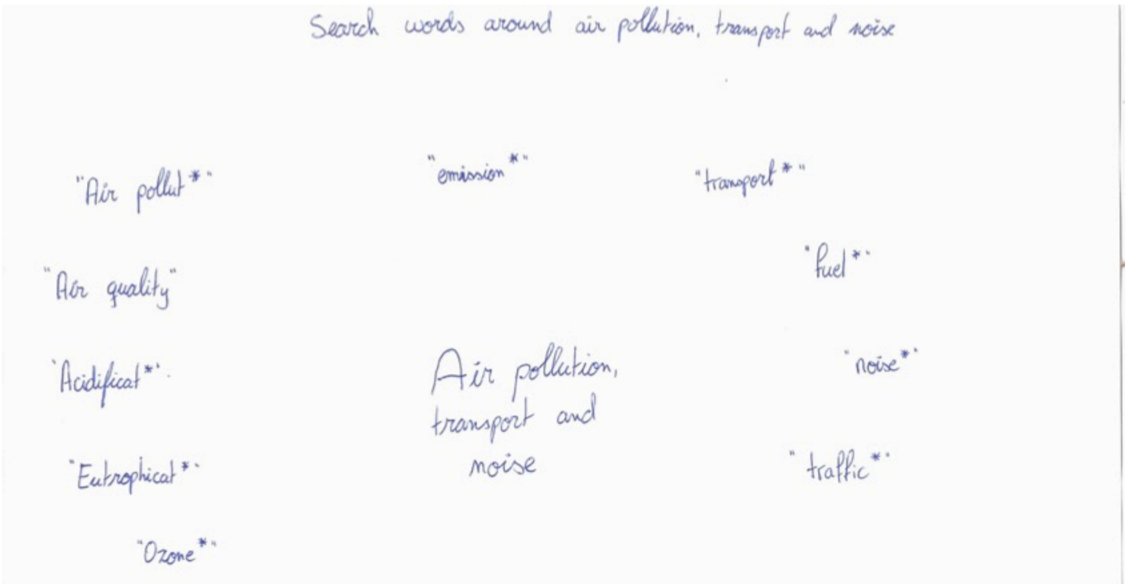
Is there something else you would like to say that is important to be mentioned in the debate around the sustainability of gene-editing?

Did you enjoy the interview?
Do you know any colleagues that I should get in contact with in the context of this thesis?
Would you like to receive the results from my study?

9. Appendix 2

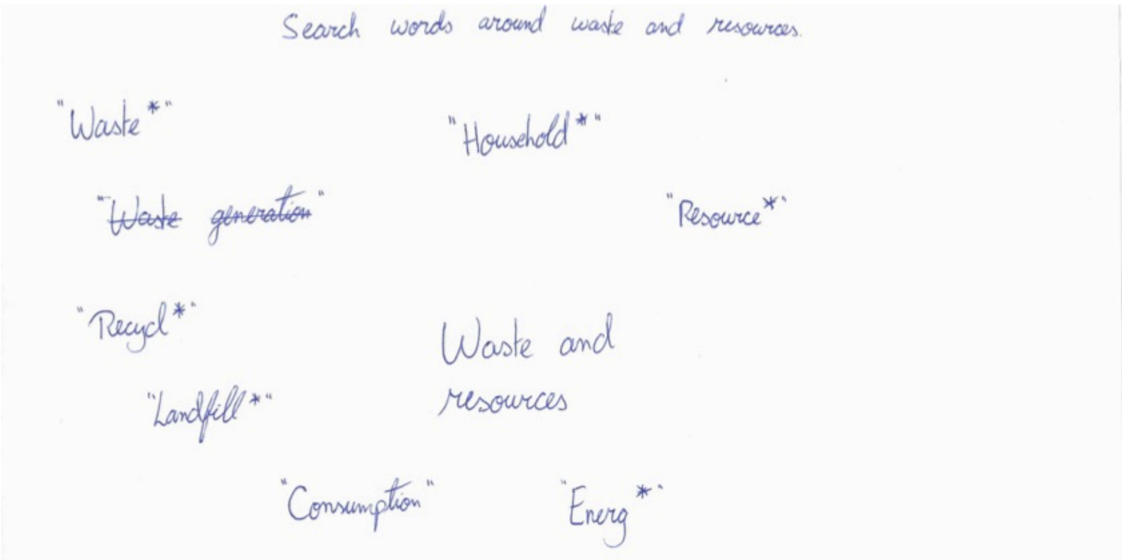
Search words around gene-editing.

Search words around air pollution, transport and noise.

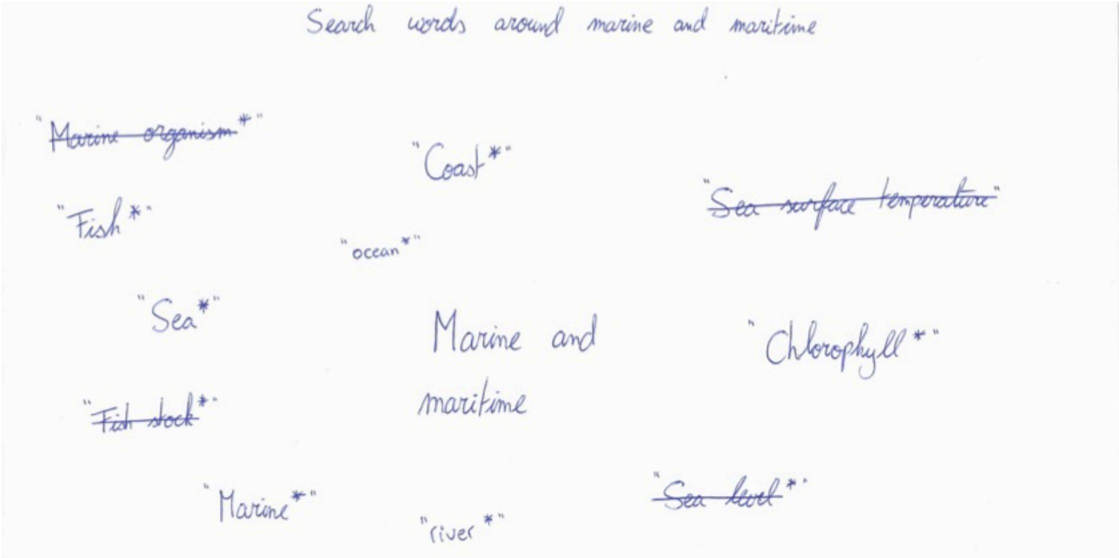


Search words around freshwater resources.

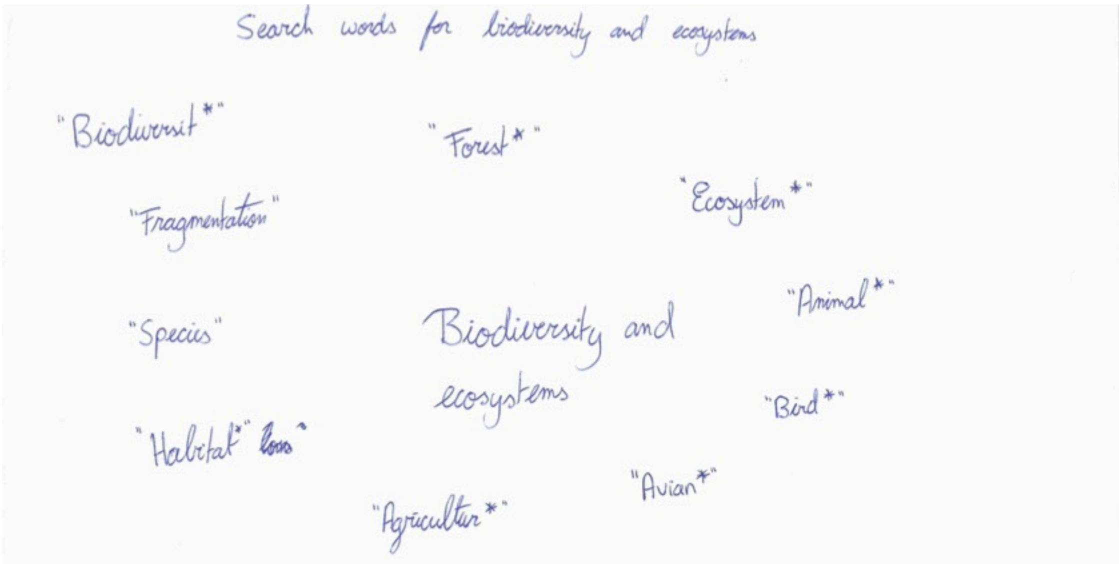
Search words around waste and resources.



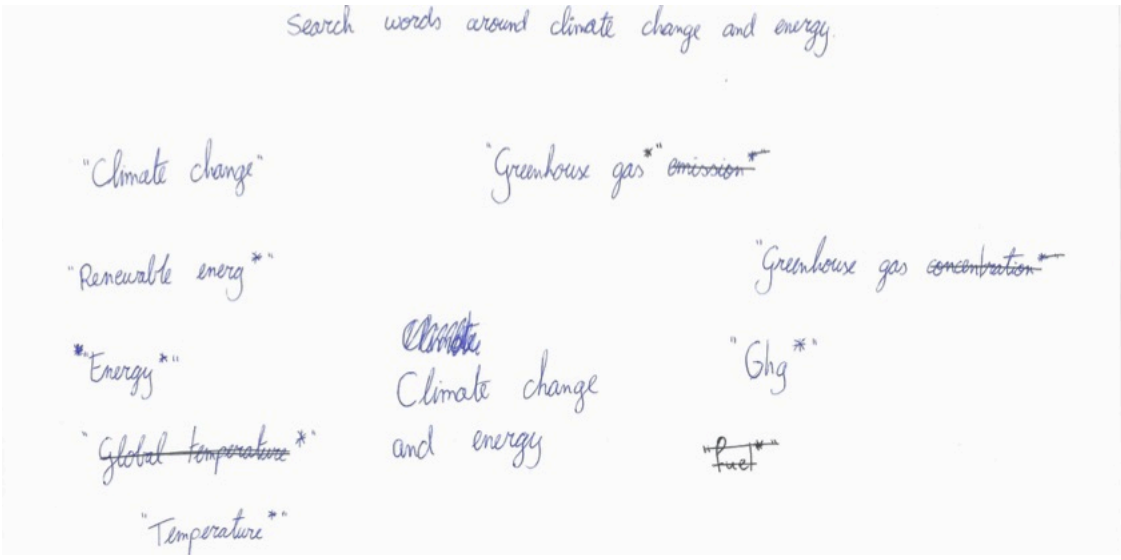
Search words around marine and maritime.



Search words around biodiversity and ecosystems.



Search words around climate change and energy.


Search words around climate change and energy.

"Climate change"

"Greenhouse gas*" ~~emission*~~

"Renewable energ*"

"Greenhouse gas ~~concentration*~~

"Energy*"

Climate change and energy

"Ghg*"

"~~Global temperature~~*"

~~"fuel*"~~

"Temperature*"