When nature noes digital: routes for responsible innovation
Routes for responsible innovation

Bruynseels, Koen

DOI
10.1080/23299460.2020.1771144

Publication date
2020

Document Version
Final published version

Published in
Journal of Responsible Innovation

Journal of Responsible Innovation

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tjri20

When nature goes digital: routes for responsible innovation

Koen Bruynseels

To cite this article: Koen Bruynseels (2020): When nature goes digital: routes for responsible innovation, Journal of Responsible Innovation, DOI: 10.1080/23299460.2020.1771144

To link to this article: https://doi.org/10.1080/23299460.2020.1771144

Published online: 19 Jun 2020.

JOURNAL OF RESPONSIBLE INNOVATION
https://doi.org/10.1080/23299460.2020.1771144

Routledge
Taylor & Francis Group

RESEARCH ARTICLE

OPEN ACCESS Check for updates

When nature goes digital: routes for responsible innovation

Koen Bruynseels

Philosophy Department, Technology, Policy & Management, T.U.Delft, Delft, Netherlands

ABSTRACT

Digitalization of biological populations and ecosystems changes our relation towards them. *In silico* representations of natural systems make them available as resources that allow for novel ways of deriving economic value. These extracted data and models also open novel routes for responsible innovation based on biological systems and derived biological data. Responsible innovation based on natural resources is explored using the common pool resource framework and using the emerging field of biodiversity sequencing as an example. Natural systems that have a vast digital representation which is shared by a community have aspects from both a natural resource commons and from a knowledge commons, but differ in their structure and dynamics. We therefore propose the concept of 'Twin Commons': the institutional arrangement of natural resources that have a tightly linked digital component which is shared and governed by a community, and that have research and innovation as important outlets.

ARTICLE HISTORY
Received 20 June 2018
Accepted 14 May 2020

KEYWORDS
Responsible innovation; twin commons; biodiversity; knowledge commons; innovation commons

Introduction

Digitalization opens up biological populations and ecosystems for human usage in novel ways. As indicated by Hess and Ostrom, the mere fact that digital technologies allow capturing aspects of biological systems that were previously uncapturable, 'creates a fundamental change in the nature of the resource, with the resource being converted from a nonrivalrous, nonexclusionary public good into a common-pool resource that needs to be managed, monitored, and protected, to ensure sustainability and preservation' (Hess and Ostrom 2007).

Commons are the institutions that govern the creation and use of common pool resources – resources that are shared by multiple stakeholders and subject to social dilemmas (Ostrom 1990). In this paper, we ask what type of commons can result from the digitalization of natural systems, and how these commons can contribute to responsible innovation based on (common pool) digitalized natural resources. The concept of common pool resources originated from the study of natural resources that are managed by a group of stakeholders and that are prone to social dilemmas (Ostrom 1999). Fishing grounds and forests are archetypical substrates of such 'natural resource

CONTACT Koen Bruynseels k.r.c.bruynseels@tudelft.nl Philosophy Department, Technology, Policy & Management, T.U.Delft, P.O. Box 5015, Delft 2600 GA, Netherlands

commons'. The members of a community extract, for instance, fish or logs from the common pool resource, which can lead to depletion of the resource if not managed. Institutes around biophysical resources that have a digital correlate have been characterized as research commons (Dedeurwaerdere, Melindi-Ghidi, and Broggiato 2016), or as knowledge commons (Strandburg, Frischmann, and Madison 2017). The first perspective targets biological data and related samples in a mainly academic research environment. The knowledge commons perspective focuses on biological data as the resource that is prone to social dilemmas.

As an alternative analysis, we propose to introduce the concept of 'twin commons': commons in which the natural resources consist of a (bio)physical reality and of a digital extract that represents aspects of this reality. At the conceptual level, this concept helps to gain more clarity about the nature and the dynamics of digitalized natural resources and their related communities, and their difference from already existing categories of commons (i.e. natural resource commons, knowledge commons, digital commons) (Section 'Digitalized natural resources as common pool resources'). Twin commons build on the concept of 'innovation commons'. As such they can shed light on innovation in natural resource digitalization initiatives (Section 'Digitalized natural resources as substrate for innovation'). A twin commons framework is proposed to cover the main aspects in public natural resource digitalization initiatives (Section 'A hybrid concept: twin commons'). Venues for responsible innovation in twin commons are explored in Section 'Responsible innovation in the twin commons'. In section 'Biodiversity sequencing initiatives – venues for responsible innovation', we discuss twin commons in the context of the biodiversity sequencing field, more specifically in the context of the setup of the recently initiated Earth Biogenome Project (Lewin et al. 2018).[1]

Digitalized natural resources as common pool resources

Natural resources, biological populations and ecosystems increasingly have a digital correlate. Molecular readout technologies now allow for characterizing the genomes of large populations, be it of humans, cattle, crops, wild plant species, up to microbes and fungi. Aerial imaging techniques allow for building high resolution and dynamic pictures of fishing grounds, geological structures, and land usage. The results are large quantities of geospatial, genetic, biochemical and phenotypic data, residing in a plethora of data repositories. Access to these data not only allows studying these natural systems in innovative ways, it can fundamentally change the nature of these systems, since they become available as 'resources' that can be mined (*in silico*, and as a consequence also *in vivo*) and utilized for human purposes. In biological systems that are already used as resources, digitalization can trigger a fundamental repurposing. Digitalization thereby generates substantial risks. It facilitates biopiracy, a situation in which information on natural compounds is used to file patents or develop products, without consent or a proper compensation of the communities that have the traditional knowledge about the related species, nor a contribution to the biotope's sustainability. Digitalization also paves the way for potentially disruptive technologies, such as for instance the application of gene drive technologies for engineering ecosystems. Digitalization of biological systems also creates substantial opportunities. Biodiversity conservation can for instance benefit from a deeper knowledge of biological diversity at the genetic level. Economic and societal opportunities lie in innovations that can be derived from the bio-data.

Shared natural resources, whether digitalized or not, are subject to problems like congestion, free riding, conflict, overuse, pollution and degradation, commodification or enclosure, and non-sustainability (Hess and Ostrom 2007). Classical economic theory predicts a 'tragedy of the commons' (Hardin 1968) as the bleak outcome of these social dilemmas. In this scenario, stakeholders collectively overuse and eventually deplete the resource in their rational pursuit to maximize individual interests. In practice however, local communities seem to be able to circumvent this grim prediction without having to revert to privatization of the resource. They do so by installing rules that organize the interactions among the stakeholders, and between the stakeholders and the resource. Ostrom termed these shared resources 'Common Pool Resources' – and defined them as 'natural or man-made resource system that are sufficiently large to make it costly (but not impossible) to exclude potential beneficiaries from obtaining benefits from its use' (Ostrom 1990). Natural resources have been framed as common pool resources when a multitude of stakeholders is involved in their management and usage. The term 'commons' originally refers to the common grounds in medieval Europe, where villagers were allowed to harvest fruits, wood, and graze their herds. Commons imply social dilemmas: conflicts between individual's rational behaviour and the group's optimal outcomes (Poteete, Janssen, and Ostrom 2010). Ostrom and colleagues studied a variety of natural resource commons. Eight institutional design principles were derived that are associated with long-during commons: clearly defined boundaries, rules that are tuned to local circumstances, participation in the rule setting and modification, monitoring of the appropriators and graduated sanctions in case of violations, conflict-resolution mechanisms, recognition of the right to self-organize by external institutions, and the organization of key activities in the commons as multiple layers of nested enterprises (Ostrom 1990).

Digitalization can substantially affect the dynamics of natural resources and the related commons by creating a second digital common pool resource that is interlinked with the natural resource. The common pool resource concept was also applied to this 'new shared territory of global distributed information' (Hess and Ostrom 2007). The main entry point was that knowledge is increasingly co-produced, co-managed and co-used by a multitude of stakeholders. Especially with the advent of the Internet it became obvious that a digital equivalent of the known biophysical commons was in the making. Digitally stored information for instance provides the commonly shared knowledge grounds for scientists and technologists. These 'Knowledge Commons' or 'Cultural Commons' revolve around common pool resources consisting of pieces of information, rather than of matter (Madison, Frischmann, and Strandburg 2010). They were defined as 'the institutionalized community governance of the sharing and, in many cases, creation of information, science, knowledge, data, and other types of intellectual and cultural resources' (Strandburg, Frischmann, and Madison 2017). Knowledge commons have some distinct features that set them apart from natural commons. Firstly, they are inherently global, since asymptotically information and knowledge are not constrained by the boundaries of a specific local community. Secondly, they concern non-subtractable resources. In contrast to for instance a fishing ground, a knowledge common pool resource cannot be depleted since knowledge does not decrease when being consumed. Nevertheless knowledge commons require a joint effort by the community of stakeholders in order to ensure production and availability of data and knowledge, to manage access rules, foster correct usage, etc. This non-subtractability makes knowledge also non-rivalrous, though the production of knowledge may depend on rivalrous input like time and money, and lead to rivalrous output like money or fame (Strandburg, Frischmann, and Madison 2017). In contrast to natural resource commons, knowledge commons need to be created before they can be shared (Strandburg, Frischmann, and Madison 2017).

The knowledge commons concept was also applied to natural systems that obtained a digital representation: genetic data (Pálsson and Prainsack 2011) (Contreras 2014), microbiology data (Uhlir 2011) and to various types of medical data (Strandburg, Frischmann, and Madison 2017). This is not surprising since biomedical and biological sciences have become data intensive disciplines. Powerful digitization techniques such as next generation sequencing and medical imaging allow for massive readout of data from biological systems. These technologies result in large amounts of biological data, residing in repositories and made accessible via Internet technologies. Framing these systems as knowledge common pool resources provides an alternative to schemes where the data or the knowledge is considered as either public or proprietary. This perspective also implies an institutional component, rather than exclusively focusing on the individual actor, invention, or piece of information. Reframing the analysis in this broader context provides a more comprehensive view when analysing processes like innovation and decision making in these complex environments (Strandburg, Frischmann, and Madison 2017). Knowledge commons have been broadly defined in this context, to cover not only knowledge but also the sustainable management of information and data (Strandburg, Frischmann, and Madison 2017).

Importantly, digitalized natural resources must be analysed neither as pure natural resources nor as pure digital resources. Rather, the commons revolving around these resources constitute hybrids made of a knowledge commons and a natural resource commons, having distinct dynamics and requiring a specific type of analysis. For instance, the production or read-out of biological data directly and intimately relates both to the biological samples as well as to the populations or ecosystems they originated from. Biological systems have been characterized as data repositories of sorts, in which massive amounts of genomic and molecular data are 'stored' and available for 'readout'. The human genome for instance has been termed in this context a natural resource, and medical genetics an extractive industry that extracts information and uses this to develop health care products (Evans 2014), (Strandburg, Frischmann, and Madison 2017). Analysing these systems as mere knowledge commons would incorrectly imply that only the knowledge aspects are to be considered and are of value. Such framing runs the risk of reducing digitized natural systems to their knowledge components, thereby undervaluing and obscuring the underpinning populations or ecosystems.

Digitalized natural resources as substrate for innovation

Digitalization of natural resources aims at knowledge generation and at deriving innovations with market value and/or societal value. Often large-scale data generating endeavours aim at deeper scientific understanding of the targeted biological systems. Digitalized natural resources therefore have been characterized as the subject of research commons. The research community dealing with the exchange of information and samples on microbial strains has been for instance described as a microbial commons

(Dedeurwaerdere, Melindi-Ghidi, and Broggiato 2016). Next to research, many large-scale initiatives also explicitly seek to foster a flourishing innovation landscape around the generated scientific data. For example, the genomic data gathered in the Genomics England initiative is intended to be used to develop predictive medicine practices (Marx 2015). The creation of a silicon-valley like cluster around Amazonian biodiversity has been proposed as a route to a new biodiversity based economy (Nobre et al. 2016). Such initiatives therefore aim at the fostering of high levels of data-driven innovation. Data-driven research differs from settings where the data are generated in order to investigate dedicated research hypotheses. This type of research focuses on exploratory rather than theory-driven experimentation (Pietsch 2015).

Innovation commons were recently proposed as a special case of knowledge commons (Potts 2018). Innovation commons were defined as institutions 'to facilitate cooperation and supply governance among a group of technology enthusiasts in order to create, under high uncertainty, a pooled resource from which the individual members of the community might seek to discover and develop entrepreneurial opportunities for innovation' (Potts 2018). The focus thus is on the peer production of information in order to derive business opportunities. Innovation commons bring the data, tacit knowledge, technologies and stakeholders together, thereby providing the conditions to spot entrepreneurial opportunities. In the innovation commons outlined by Potts, the commoners gather around the question how to transform an idea into an innovation. The preconditions for such innovation commons thus are a new idea, invention or technology; distributed information and tacit knowledge that are related to the idea; and uncertainty about whether that idea provides a concrete entrepreneurial opportunity – i.e. the knowledge problem that is inherent to this early innovation stage (Potts 2018). Examples of innovation commons are open source software initiatives and hacker spaces that focus on novel technologies like blockchain and synthetic biology. Innovation commons are efficient in minimizing the transaction costs of discovering entrepreneurial opportunities present in the community and its resources (tacit knowledge of its members, data, technologies). They thereby solve a collective action problem: given the uncertainty that investments in this early phase effectively will yield viable innovations, the innovation commons thrive on the rules and control mechanisms that are set by the community itself. More formal organizations are claimed to be less efficient in managing the transactions in this early stage of innovation.

Communities around digitalized natural resources meet the preconditions for an innovation commons. They concern expert knowledge about the generated data: how the data are structured, what already is known about the data, what potentially can be derived from the data. This tacit knowledge is distributed across various experts and proto-entrepreneurs, that form a community around the given topic and datasets. Digitalized natural resources, however, provide a different flavour of innovation commons. Innovation communities centred around biological data are often long-standing and imply professional roles, as for instance in microbial research commons (Dedeurwaerdere, Melindi-Ghidi, and Broggiato 2016) or the genome commons (Contreras 2014). This in contrast to the hacker spaces that provided the archetype for Potts' innovation commons. Hackers spaces are short lived and populated with technology enthusiasts. In contrast, the Human Genome Project for example ran for over a decade, steadily releasing new data in the genome commons. The commons related to digitalized natural resources are not purely pre-entrepreneurial, pre-firm nor pre-market. Data are generated over years and thereby give rise to a continuous valorization stream. The shared resources in innovation commons are the technologies and the knowledge that are required to derive innovations from them: knowledge about the market, about how to set up a successful enterprise around an innovation, about regulatory boundaries, etc. The shared resources in digitalized natural resource commons also encompass the natural resource and the data resources that are derived from it. The microbial research commons for instance consist not only of shared microbial sequence data, but also of microbial collections (Dedeurwaerdere, Melindi-Ghidi, and Broggiato 2016). There are therefore clear differences with the innovation commons model as described by Potts. The question thus is how to describe the commons that result from the digitalization of natural systems in a way that accurately captures their innovation dynamics. In the next section we attempt to do this by building on the previously described commons concepts.

A hybrid concept: twin commons

Digitalization of biological systems concerns three interconnected resources. At the basis is the digitalized biological system, which becomes available as a *natural resource*. The derived biological data constitutes a *knowledge resource*. The conglomerate of entrepreneurial ideas, technologies and related knowledge about technical possibilities, and tacit knowledge about the data in general can function as an *innovation resource* from which opportunities can be identified. Each of these resources are prone to collective action problems since they are shared among multiple stakeholders. Neither markets nor state interventions alone are able to solve these issues of free riding, excessive resource usage, etc. For that reason, one can see that many natural resource digitalization initiatives in practice have the characteristics of commons (Madison, Frischmann, and Strandburg 2010) (Dedeurwaerdere, Melindi-Ghidi, and Broggiato 2016). As indicated in previous section, digitalized natural resource commons have characteristics of natural resource commons, knowledge commons, research commons and innovation commons. A commons concept that contains elements from all aforementioned types is thus required.

We propose 'Twin Commons' as a framework to denote the institutional arrangement of natural resources that have a tightly linked digital component which is shared and governed by a community, and that have research and innovation as important outlets. Twin commons comprise a twin resource (a natural resource and its digital representation, linked via technologies) that is managed by a group of stakeholders as a common resource (see Figure 1). These elements provide an environment where innovation can take place. Twin commons consist of the following five components:

(1) **(Bio)physical system**: the natural resource, the particular ecosystem, or the population of biological individuals that are in scope as resource to be managed by the group of stakeholders.
(2) **Digital and knowledge counterpart**: the digital representation of the (bio)physical system. This can be the collection of genomic sequences derived from samples and related inferences about their relations to phenotypes, models of biological mechanisms and pathways, theories about potential applications, etc. This digital model represents certain molecular and phenotypic aspects of the biophysical system.

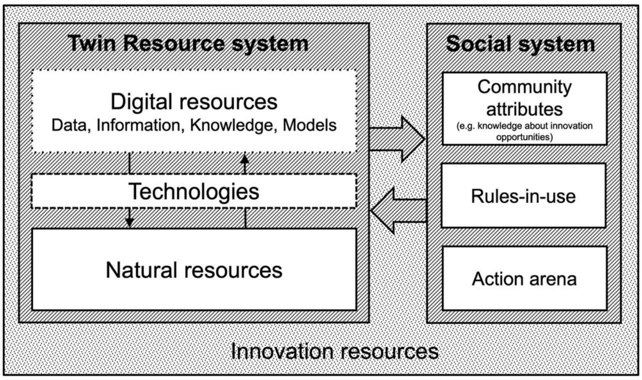

Figure 1. Components of a Twin Commons. The components in the Institutional Analysis and Design framework (Ostrom 2005) are presented in an aggregated way under 'Social system', and put in relation to resource components in the commons (the biophysical system; its digital representation; and the technologies that mediate the relation between both). Innovation resources comprise all the components in the twin commons.

(3) **Bridging technologies**: technologies that provide a bridge between the (bio)physical system and its digital representation. This comprises the set of already available technologies that allow for deriving data from the bio-physical system (e.g. genome sequencing technologies, sensor data, computational methods to analyse the data), and the set of technologies that allow to change the bio-physical system based on the digital representations (e.g. genomic editing technologies like CRISPR-Cas).
(4) **Social system**: the system that manages the *natural*, *digital*, and *innovation* resources as a commons. Along the lines of the Institutional Analysis and Development framework (Ostrom 2005), one can further distinguish the rules, the action arena and the attributes of the community. Concerning the attributes of the community, its boundaries are defined by topic, rather than by physical location as is the case for natural resource commons. Often the data are produced, managed and used by a variety of stakeholders. Submission, management and usage of the data are subject to some of the social dilemmas that are characteristic of a commons. Researchers that contribute data to the resource want to avoid the free-rider problem, and ensure that they obtain what they see as the proper benefits from their efforts. Successful commons often develop rules to efficiently identify and sanction free-riders (Poteete, Janssen, and Ostrom 2010). Rules, be them formal or informal, have an impact on the interactions between the actors. Data submission and access rules for instance vary across data repositories and demarcate the boundaries of the commons.
(5) **Innovation common resources**. Twin commons provide the raw material and the social structures that help enable innovation: the pool of shared or tacit knowledge about technologies, data, and related innovation opportunities, together with the access to the natural and digital resources.

The innovation aspect of twin commons has characteristics of the innovation commons as described by Potts (Potts 2018). Twin commons bring together a heterogeneous community of funders, researchers and entrepreneurs that together construct innovation opportunities (including both technical and business opportunities). Twin commons do this specifically by bringing the stakeholders together around a scientific data gathering initiative. Access to a natural resource and to digitalization technologies is a prerequisite for constructing the pool of shared biological data. This interplay between the biophysical, the informational, and the societal aspects of natural resources is key to understanding the innovation dynamics in twin commons. Given the fact that natural systems evolved over billions of years, biological datasets can only shed light on a very tiny fraction of the complex biological reality. The primary source of innovation opportunities is in the biological system. Focusing solely on the knowledge component therefore would miss out on the importance and the inherent value of the natural system in the innovation process. Twin commons tend to be long standing. Construction of the shared pool of biological data and knowledge takes time and resources. Twin commons therefore are not entirely pre-market. Tech transfer departments and public-private partnerships are often involved. The commoners can include amateur enthusiasts that look for business opportunities, but often consist of professional scientists, business developers, programme managers, etc.

In short, twin commons in biology comprise digital information (for instance sequences and their annotation); the related biological populations, ecosystems, and the derived biological material; and a community that uses these resources in the identification of innovation opportunities and that applies self-governance to sustainably manage the commons pool resources. Examples are ubiquitous in biological sciences, though the focus is often put on the knowledge commons aspect. Human genomic data was for instance framed as a resource for knowledge commons (Evans 2017). The tight link between human populations, derived genomic data, and innovation potential calls though for a setting where all elements are taken into account, in order to avoid usage of genomic data without a contribution to those populations (Hardy et al. 2008). A similar situation can be observed with respect to biodiversity data, where a social production model for both the sharable goods and the derived information was suggested. In the studied case, the microbial data commons hinge on the materials commons, though the impact of regulators on sharing behaviour substantially differs in both domains, with a higher reluctance to share data than materials (Dedeurwaerdere, Melindi-Ghidi, and Broggiato 2016).

Responsible innovation in the twin commons

Innovation constitutes an intrinsic part of many large-scale biological data generating efforts. The vast impact these innovations can have on society and on the natural world sharply raises the question of responsibility. What are the venues for responsible innovation in a twin commons? Responsibility is a rich concept that goes beyond the attribution of blame for undesired events, and also encompasses a virtue ethics component. Interpreted as such, responsibility is a character trait of members in an innovators community (van de Poel and Fahlquist 2013). Moreover, it has been argued that responsibility is not something that needs to be added to innovation, but provides both the very foundation and motivation for innovation (Bergen 2017). These foundational and motivational relationships between responsibility and innovation are, on the one hand, already visible as inherent aspects of twin commons. Responsibility plays an instrumental role in the management of every common pool resource. It provides a necessary complement to rational self-interest of individual stakeholders and thereby is instrumental in avoiding a tragedy of the commons. Experimental research showed that participants in social dilemma games are willing to give up part of their monetary benefits, in order to get the capability to punish players that misbehave. In successful commons, irresponsible behaviour towards the commons or towards the community of stakeholders is carefully monitored and sanctioned (Poteete, Janssen, and Ostrom 2010). In the case of twin commons, collective responsibility may take the form of implicit or explicit rules on for instance data release policies, data quality, extraction of intellectual property. Collective responsibility may also play an important role in constructing the innovation commons. These projects often aim at contributing to solutions for wicked problems, providing an overall focus on for instance sustainability and biodiversity conservation, or the feeding a growing world population.

On the other hand, tragedies of the commons nevertheless occur. Bergen thus points to a third relationship between responsibility and innovation in which 'the outcomes of innovation form the structures through which we can actually work towards justice' (Bergen 2017, 362). The question is how one can better ensure societal value by the deliberate inclusion of values in the innovation process, so that technologies evolve in a direction that is beneficial for society as a whole, and negative outcomes are avoided. Responsible innovation has been proposed as a conceptual framework to enable this. In a broad sense, it is defined as 'taking care of the future through collective stewardship of science and innovation in the present.' (Stilgoe, Owen, and Macnaghten 2013). The emphasis of collective stewardship can also be found in the definition of von Schomberg (2013). Other definitions focus on the translation of value considerations into functional requirements in the innovation process. Moral evaluation of the consequences of the possible actions during innovation should lead to requirements that are included the innovation process (van den Hoven et al. 2013). In short, the rules, interaction mechanisms, and values that characterize a twin commons, can provide the context for innovation to occur in a responsible way.

Theories of action in commons (Poteete, Janssen, and Ostrom 2010) can provide a framework to spell out the notion of collective stewardship in responsible innovation. The Institutional Analysis and Development developed by Ostrom and others (Ostrom 2005) allows analysing stakeholders and their relations in a commons and has already been linked to responsible innovation (Kuzma et al. 2017). Design principles for a sustainable management of common pool resources also apply to commons where innovation assets (biological samples, data, knowledge, etc.) are a shared resource. Innovation commons for instance require mechanisms to avoid that free riders file intellectual property based on shared resources. Collective stewardship in a responsible innovation approach often encompasses the involvement of a broader set of stakeholders in the innovation process. In industrial settings, information constitutes a competitive advantage, and stakeholders strongly differ in the power they can exert (Blok and Lemmens 2015) (Bergen 2017). In a twin commons, all stakeholders participate in one way or another in the governing of the shared resources. Stakeholder involvement in a commons is therefore not something that is injected in an already existing innovation process, but an intrinsic and structural part of the innovation process.

Alongside technical innovations, twin commons also allow for framing social innovations. Social innovations have not been a primary focus in the responsible innovation literature (Lubberink et al. 2017) (Blok and Lemmens 2015) (Bergen 2017). Commons, with the focus on solving social dilemmas, provide an established framework to structurally include social innovations in the sustainable management of a natural resource. The interaction with digitalized natural systems challenges the *status quo* and calls not only for technical but also for social innovations. The national implementations of the Nagoya Protocol for instance can be regarded partially as social innovations. Mechanisms for a fair sharing of benefits needed to be fundamentally rethought – in light of both the natural resources that could be distributed globally, potentially providing significant income from innovation, and the global community that could share information via digital routes.

Twin commons also provide a conceptual instrument to pinpoint more precisely which areas of responsibility to consider in relation to the innovation process. One has responsibilities towards the natural systems in scope, for instance the responsibility to not negatively impact the sustainable management of the resource. Another example is the responsibility to respect the inherent value of the resource during the innovation process. One also has responsibilities towards the derived data and knowledge, for instance the responsibility to contribute to sustainable management of the data resource, the responsibility to guarantee privacy in case of personal data, or the responsibility to contribute information to the data resource. Responsibilities regarding the mediating technologies can include innovating in fields that contribute to the sustainability of the natural resource, for instance improved management of a biotope via smart applications based on sensor data. Responsibilities towards the community of stakeholders include a fair distribution of the value derived from innovation, especially when commercial initiatives are derived from publicly funded initiatives.

Last but not least, the different components of a twin commons provide an instrument to make explicit what values are at stake in the commons and its innovation processes. Innovations related to twin commons often concern emerging technologies, disruptive innovation, dual use technologies and/or control dilemmas (Collingridge 1980), (Owen et al. 2013), all of which can lead to value contestation or neglect. Mapping values at stake in twin commons is an important step toward achieving responsible innovation. Values influence which innovations are pursued when applying data-derived insights. They constitute the moral context in which innovations occur including innovations related to digitalized natural resources. For example, a synthetic biology route was used to produce the antimalarial agent artemisinin using a novel route with the aim to make antimalarial treatment more available for patients in developing countries (Paddon and Keasling 2014). Similar technologies are also used for the production of enzymes for washing powder, or for the conversion of crop residues into biofuel, aiming at economic benefits but also at a decreased impact on the environment. In some cases the impact on global natural commons is potentially very high, as in the case of gene drives technologies. Such cases show that values – whether embedded in governance measures or in research ethics – and public deliberation are pivotal (Oye et al. 2014). The components of a twin commons constitute areas where values impact the innovation process. As such, they can facilitate responsible innovation in cases of epistemic insufficiency where it is difficult to anticipate the impact of innovations (Blok and Lemmens 2015). For example, embedding of values like the preservation of biodiversity (Lewin et al. 2018) or more instrumentally data ethics values like correctness and openness of data (Floridi and Taddeo 2016) provides the context in which innovation occurs.

Biodiversity sequencing initiatives – venues for responsible innovation

In this section we apply the twin commons concept and illustrate its relation to responsible innovation by considering the emerging field of biodiversity sequencing, as exemplified by the recently initiated Earth Biogenome Project. The Earth Biogenome Project aims at sequencing a vast representation of eukaryotes, comprising all known plants and animals (Lewin et al. 2018). The project is analogous to the Earth Microbiome Project (The Earth Microbiome Project Consortium 2017), another large-scale biodiversity sequencing project that charts microbial communities in habitats spread across the globe. Biodiversity constitutes an important source of innovation opportunities (Lewin et al. 2018) (Nobre et al. 2016). Efforts to map genetic diversity in all different kingdoms of life, including human genetic diversity, aim at this innovative potential, including the development of novel drugs, molecular biology tools, bioprocesses, and improved agricultural production. Sequencing of varieties of important crops like rice and corn for instance provides a rich resource for breeding (Varshney, Terauchi, and McCouch 2014). Twin commons can shed light on challenges and opportunities in biodiversity sequencing based responsible innovation. The tension between local ecosystems and biological sample collections versus globally distributed digital sequence information testifies to the importance of the relation between material commons and data commons. Resources (samples, sequence data) in these projects often constitute shared resources that are subject to collective action problems. Next to this, they provide the material for (bio)data-driven innovations that can vastly impact the natural world and society.

Biodiversity sequencing project resources are twin resource systems. The Earth Biogenome Project concerns a natural resource (plant, animal and fungal species from various environments across the globe) and a digital resource (the metadata that describe the sample and measured parameters, the genomic sequence reads, and derived data). The digital resource is linked to the organisms in their ecosystems with technologies (sampling technologies, DNA sequencing technologies, genome editing technologies). Genomics data are not fully analogous to the data found in digital commons (Pálsson and Prainsack 2011). Genomics data are embedded in biochemical molecules in biological beings, *and* partly available as representations of nucleotide sequences in data repositories. Sample acquisition provides the bridge between biotopes and digital sequence information. Organization of sample acquisition at a global scale builds upon multiple twin commons in case of the Earth Biogenome Project, by relying on a conglomerate of dedicated initiatives that organize their own sample collection. The Darwin Tree of Life project for example collaborates with multiple organizations, like botanical gardens and academic institutions, to gather samples from the British islands. Nesting of smaller locally funded commons (for instance the Darwin Tree of Life project, focusing on specific biotopes) into larger commons (the Earth Biogenome Project in this case) provides opportunities for a distributed funding of this large initiative, by breaking it down to individually funded local initiatives.

Samples tie data to a certain physical location or specific biological entity: the biotope or the organism from which the data were derived from. This provides a tension with the nature of electronic data, which can be easily distributed globally. Taking locality into account however is necessary to ensure fair access to the data and related benefits, for instance the benefits derived from innovations. Access and benefit sharing is the focus of the Nagoya protocol, which is a global protocol that is implemented on the national level. The protocol's objective is to foster a fair distribution of the benefits derived from biodiversity genetic resources and from traditional knowledge about these genetic resources. This entails the regulation of the access to genetic resources, access to technologies, benefit sharing obligations, and compliance with local regulation (Convention on Biological Diversity 2010). Brazil implemented it's own framework to regulate access to genetic heritage and associated traditional knowledge for purposes of scientific research, bioprospecting, and technological development. A national system of genetic resource management and associated traditional knowledge (SisGen) was put in place to facilitate compliance with the legislation, by supporting the registration of access, shipment or exploitation of genetic material and associated traditional knowledge. The federal government is the recipient of the benefit sharing via the National Fund for Benefit Sharing. The money in this fund is intended for a multitude of purposes, amongst which the sustainable management and conservation via support for indigenous people and traditional farmers. How exactly this fund will contribute to biotope preservation (for instance by preventing deforestation in the Amazon basin), however, needs to be seen.

Considering these as twin resource systems provides a way to bring this in the scope of management. The Amazon Bank of Codes and the Amazon Third Way Initiative (Nobre et al. 2016) aim to tightly connect the Amazon biotope to its derived data and to the innovation community in order to support the sustainable management of these resources. Blockchain technologies will be used to track usage of genetic data derived from the Amazon biotopes, together with the generated IP assets, and record the provenance, rights and obligations related to the usage of these twin resources (Lewin et al. 2018).

The twin resources in public biodiversity sequencing projects are in practice managed as commons. Managing the construction and usage of a biodiversity sequencing project implies heterogeneous stakeholders and a proneness to social dilemmas. Biodiversity sequencing initiatives have sometimes been framed as commons. For instance, the communities around microbial databases and microbial biodiversity have been studied as commons (Dedeurwaerdere, Melindi-Ghidi, and Broggiato 2016) (Hess and Ostrom 2007), moreover commons were proposed as a strategy to design this research field (Uhlir 2011). In the medical field, the knowledge commons framework was applied to human genomics data, population biobanks, cancer biology, neuroscience data, and data on rare diseases (Strandburg, Frischmann, and Madison 2017). The Earth Biogenome Project (Lewin et al. 2018) shows that multiple stakeholders are involved in the rule setting and management of both the natural resource and its derived genomic data. Its governance structure will include representatives from government, private industry, civil society, international organizations, private foundations, and participating research communities and organizations.

The stakeholders in a twin commons engage in a complex web of interactions to manage the resource and distribute the benefits. Framing biodiversity sequencing projects as a twin commons emphasizes the (technology-mediated) connection between the biological resources (be it botanical gardens, natural history museums, microbial collections, or real biotopes like the Amazon rain forest) and the derived data and knowledge. Natural resource commons tend to be local and have rather clearly defined community boundaries, while knowledge commons tend to be global. Biodiversity sequencing programmes have characteristics of both. In case of the Earth Biogenome Project (Lewin et al. 2018) a global community of academics and companies will have access to the information. But local communities in for instance the Amazon basin should also profit from the revenue streams that these global parties generate, and from local development of scientific know-how.

Framing biodiversity sequencing initiatives as twin commons also embeds the notion that interactions between the actors in the commons, and between these actors and the natural resource, are mediated by technologies. For instance, in the Amazon Bank of Codes project, blockchain technologies are proposed as a technology to track the relations between the biological origins and their derived data, and to the track the interactions of stakeholders with these data. Such technologies would allow registering both the rights and the duties of stakeholders in a distributed setting, providing an instrument in the practical implementation of the Nagoya protocol. Values embedded in blockchain technologies (the fact that one cannot tamper with the information, and that the information can be globally accessible) thus support the fair sharing of benefits derived from innovations with the communities from which the data were derived. Properly designed technology can support common formation by supporting design principles in Ostrom's commons framework, for instance by lowering the cost of implementing and managing clearly defined community boundaries, monitoring of the community members, and collective choice arrangements that allow most participants to contribute to decisions (Williams and Hall 2015).

Digitalization allows for quantification and transparency and can thereby directly support better management (although it could also lead to more intensive exploitation) of a natural resource. In non-digitalized natural resources it is often hard to know exactly how much is extracted from the commons. With the aid of sensors, databases and dashboards one can much better quantify resource usage and make this transparent to the entire community of stakeholders. Next to this, the addition of social software components can provide a binding factor for an otherwise anonymous and global community. Norms and values can be embedded in the structure of such social software environments. Tools can for instance be embedded for monitoring and punishing free-riders, for the appraisal of contributors, for a fair distribution of benefits, and for an open forum for deliberation about rules and standards. The types of commons that result from sequencing initiatives vastly differ. This opens up multiple venues for responsible innovation through attention to funding regimes, the definition of the boundaries of the commons, and the ways participants and other stakeholders are involved in the commons.

Biodiversity sequencing projects target innovation. Biodiversity sequencing projects are typically structured as research communities with valorization and technology transfer outlets. Biodiversity sequence data constitutes a rich source for innovative applications in a broad range of human endeavours: health care, production of fine chemicals and biofuels, bioremediation, agriculture, biomaterials, etc. About half of the FDA-approved drugs that are on the market are derived directly or indirectly from natural products (Katz 2011). Most of the genetic engineering tools that are available to biotechnology are derived from nature. Enzymes like reverse transcriptases and restriction enzymes have given rise to entire industries in health care, agriculture and white biotechnology. Human biodiversity at the genetic and the metagenomic level is also a rich substrate for developing innovative diagnostic and therapeutic tools. Population genomics initiatives are mapping biodiversity in entire human populations, in order to develop novel health care approaches.

And yet, the rapid loss in nature's biodiversity constitutes one of the so-called 'wicked problems' of this century. The rate of extinction of species is estimated to increase about five times in the near future as compared to the recent past (Johnson et al. 2017). One of the main causes is overexploitation by natural resource-intensive industries (Johnson et al. 2017). Significant loss of natural habitats and related biodiversity will lead to a definitive loss in natural capital, and eventually to ecosystem instability. Such loss in natural capital would vastly reduce the ability to meet the grand challenges related to the growing world population.

Some claim that developing new economic models that are based on biodiversity could provide a major opportunity to make nature conservation compatible with economic growth (Rodríguez, Rodrigues, and Sotomayor 2019) (Nobre et al. 2016). Such models would rely heavily on biodiversity-based innovation. This strategy is pursued for instance in the 'Third Way', proposing to

> aggressively research, develop, and scale a new high-tech innovation approach that sees the Amazon as a global public good of biological assets and biomimetic designs that can enable the creation of innovative high-value products, services, and platforms for current and for entirely new markets by applying a combination of advanced digital, material, and biological technology breakthroughs to their privileged biological and biomimetic assets. (Nobre et al. 2016)

The construction of a biodiversity database at the DNA sequence level in this case is an explicit strategy to value the related natural resources in a fundamentally different way, and to transform the old resource-intensive industries and agricultural practices into a new bio-based economy that preserves the Amazon's ecosystem. Commons can facilitate the enablement of such new economic models, by providing alternatives to the classical dichotomy between state control and the market, by clustering the resources that are needed for innovation (biological materials, data, knowledge, ideas), and by providing a context to frame not only technical innovation but also social innovation (via the development of institutions that allow for collective self-governance).

Analysing biodiversity sequencing projects as twin commons offers routes towards responsible innovation. Responsibility during the innovation process has very different flavours across the different biodiversity sequencing related activities. Responsible ways of dealing with innovation in the Earth Biogenome Project focus on fair and broad access to the data, and fair sharing of the benefits derived from innovations. In the synthetic biology community, a strong emphasis is put on openness in the data and the approaches, on a copy-with-pride mentality rather than patenting strategies (Torrance 2017), and on safety – since this potentially concerns dual-use technologies (Wang and Zhang 2019).

Inclusion of stakeholders in the innovation process is one of the conceptual dimensions of responsible innovation (Burget, Bardone, and Pedaste 2017). In biodiversity sequencing projects it can be challenging to install stakeholder involvement in the early innovation steps to clarify the norms and values at stake and to align them with what is societally preferable. Innovation is inherently characterized by information asymmetries and power imbalances, since innovation is pursued to create a competitive advantage and generate intellectual property (Blok and Lemmens 2015). Stakeholder involvement during early innovation steps (especially when related to corporate environments) can benefit from the collective self-regulation characteristics of commons. Responsible behaviour can be fostered by deliberate inclusion of values in the structure and workings of the commons. This can be done via the values that underpin the creation of the common resources, for example the values of sustainability and of biodiversity conservation in the case of biodiversity sequencing initiatives.

Values are also inherent to the rules that apply when valuable innovations are derived from the data. Since heterogeneous stakeholders together construct an environment for the identification of opportunities, stakeholder involvement is at play in setting the rules and in the values that are pursued in the innovation commons, rather than in each individual innovation step. The so-called pharmaceutical commons testify to these dynamics (Lezaun and Montgomery 2015). Deliberation of the values at stake in the commons (via the commoner's community), and inclusion of values in the rules that govern the common, provide two clear venues for responsible innovation in public biodiversity sequencing initiatives. Next to this, Value Sensitive Design (van den Hoven 2013) provides a way to embed values in the technologies used in the twin commons. Value sensitive design comprises the deliberate inclusion of values in artefacts (van den Hoven 2013). One can target the inclusion of values in the artefacts that are the output of the innovation process, as for instance in the development of washing powder enzymes that work at lower temperatures and thereby contribute to sustainability. Another route is to consider the values that are embedded in the technologies that mediate the relation among the natural resource, its data representation, and the community of stakeholders. Values can for instance determine the access to the resources and the boundaries of the community. Blockchain technologies can ensure traceability and validity of the contracts and interactions.

The twin commons framework can be used to map out the community of stakeholders involved in commons-based innovation. When analysing genomic data repositories as genome commons, the different stakeholders have been described in terms of funders, data generators, data intermediaries, data subjects, the public, data users and scientific leaders (Contreras 2014). The latter two groups are formally tasked with the scientific aspects of the innovation, but it is clear that all stakeholder groups contribute to the innovation dynamics. Stakeholder heterogeneity poses a challenge in managing common pool resources (Poteete, Janssen, and Ostrom 2010) given the asymmetry in investments and benefits.

The twin commons framework can also be instrumental in the clarification of the values to be pursued during responsible innovation. Framing biodiversity sequencing projects simply as knowledge commons carries the risk that social dilemmas amongst the actors are considered to be merely about the information, not also about the ecosystems that underpin the information. Such framing also misses out on the fact that innovation happens not only in the conceptual space, but requires the interaction with the natural system. A twin commons implies that *both* the natural and the informational components are valued as intricate parts of the resource system. It avoids the virtualization and thereby depreciation of the natural system when dealing with it.

Conclusion

Natural systems are being increasingly digitalized by wireless sensors, imaging technologies, molecular readouts, and other means. This digitalization makes these natural systems available in unprecedented ways. While the digital resource provides fertile ground for research insights and innovations, digitalized natural resources pose specific opportunities and challenges. The main question explored here is how to provide the right environment for research and innovations – one that develops innovations in a societally beneficial ways while mitigating risks.

In this paper we propose twin commons as framework and relate it to venues for responsible innovation. We define twin commons as digitalized natural systems that constitute a common resource managed by a group of stakeholders, have a proneness to social dilemmas, and have research and innovation as their main focus. The twin commons framework builds on natural resource commons (Ostrom 1990) and on knowledge commons (Hess and Ostrom 2007). Twin commons display characteristics of both types of commons, since they concern a twin resource: a digital resource that is derived from a natural resource. For instance, ecosystems are geographically local, but the derived data have (tangentially) the character of a *global* resource. The natural system is a given, while the digital resource is produced. Bringing both together in one framework makes this tension explicit. The twin commons framework also builds on the innovation commons (Potts 2018). Twin commons are formed in order to provide a fruitful environment for research and for marketable innovations. Many of the large biodiversity sequencing initiatives for instance aim at the generation of knowledge, but also on the fostering of a biotech-economy. Twin commoners, however, tend to be professionals who gather in long term initiatives, in contrast to innovation commons (modelled on hackerspace communities) which tend to be short lived and composed of enthusiasts pre-market (Potts 2018). More empirical research is needed to analyse the variety of public natural resource digitalization projects, for their stakeholder composition, community structure, spatial and time component, and innovation dynamics. As an outlook, cross learning over the diverse biodiversity sequencing projects can be highly valuable. Along the lines of common pool resource analysis executed on natural resource commons by Ostrom and others, one can expect to derive characteristics of successful and responsibly innovative commons.

The twin commons framework can be instrumental when pursuing the responsible digitalization of natural resources. One aim of responsible innovation is to align innovations with the values that are preferred by stakeholders. Twin commons provide multiple venues to assist in reaching that goal. They provide an instrument to map the stakeholders and the interactions and rules that are set amongst them. They also provide a structure to map the values that are implicitly or explicitly present in the innovation environment. Finally, they provide a tool to engineer the innovation environment, for instance by embedding values, or by making deliberation about values a design component of the community. This helps in guiding innovation in environments where early-stage stakeholder involvement is difficult to foster, for instance in industrial settings where information asymmetries can be key to competitiveness. A responsible innovation approach in digitalized natural resource commons can combine risk analysis and the alignment of innovations with transparently deliberated values. Further research in concrete natural resource digitalization projects will be needed to derive practical formulas for responsible innovation in these systems.

Interactions among stakeholders in twin commons are digitally supported, given the often global character of these communities. This provides interesting venues for a Value Sensitive Design approach, in which values are embedded in the systems that support electronic interaction among stakeholders and between stakeholders and the data. Tracking of the usage and of the derived benefits can for instance be done using blockchain technologies, as was proposed for the Amazon Base of Codes. Here also, further conceptual and empirical research is needed to identify principles for organizing fair and sustainable commons that provide innovations that are aligned with societally preferred directions and that mitigate the related risks.

Note

1. This project was launched in November 2018 and aims at sequencing all eukaryotic biodiversity within a decade. This endeavour requires a massive sample collection and sequencing initiative, encompassing multiple institutions and research communities from across the globe. The data will be made available as a global resource for research and innovation. The project therefore will need to develop institutions to deal with commons dilemmas.

Acknowledgements

I want to acknowledge the conceptual input and the feedback from Jeroen van den Hoven and Filippo Santoni de Sio

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributor

Koen Bruynseels is Bio-Engineer, studied philosophy at the Institute of Philosophy (K.U.Leuven), and obtained a Ph.D. in Biomedical Sciences (K.U.Leuven).

ORCID

Koen Bruynseels https://orcid.org/0000-0001-7133-3978

References

Bergen, J. P. 2017. “Responsible Innovation in Light of Levinas: Rethinking the Relation Between Responsibility and Innovation.” *Journal of Responsible Innovation* 4 (3): 354–370.

Blok, V., and P. Lemmens. 2015. “The Emerging Concept of Responsible Innovation. Three Reasons why it is Questionable and Calls for a Radical Transformation of the Concept of Innovation.” In *Responsible Innovation 2: Concepts, Approaches and Applications*, edited by B.-J. Koops, I. Oosterlaken, H. Romijn, T. Swierstra, and J. van den Hoven, 19–35. Berlin: Springer international.

Burget, M., E. Bardone, and M. Pedaste. 2017. “Definitions and Conceptual Dimensions of Responsible Research and Innovation: A Literature Review.” *Science and Engineering Ethics* 23 (1): 1–19.

Collingridge, D. 1980. *The Social Control of Technology*. London: Francis Pinter Ltd.
Contreras, J. L. 2014. "Constructing the Genome Commons." In *Governing Knowledge Commons*, edited by B. Frischmann, M. Madison, and K. Strandburg, 99–136. Oxford: Oxford University Press.
Convention on Biological Diversity. 2010. *Nagoya Protocol*. Accessed 2020. https://www.cbd.int/abs/about/.
Dedeurwaerdere, T., P. Melindi-Ghidi, and A. Broggiato. 2016. "Global Scientific Research Commons Under the Nagoya Protocol: Towards a Collaborative Economy Model for the Sharing of Basic Research Assets." *Environmental Science & Policy* 55: 1–10.
Evans, B. J. 2014. "Mining the Human Genome After Association for Molecular Pathology v Myriad Genetics." *Genetics in Medicine* 16: 504–508.
Evans, B. J. 2017. "Genomic Data Commons." In *Governing Medical Knowledge Commons*, edited by K. J. Strandburg, B. M. Frischmann, and M. J. Madison, 74–101. Cambridge: Cambridge University Press.
Floridi, L., and M. Taddeo. 2016. "What is Data Ethics?" Philosophical Transactions of the Royal Society A 374: 2083.
Hardin, G. 1968. "The Tragedy of the Commons." *Science* 162 (3859): 1243–1248.
Hardy, B.-J., B. Séguin, R. Ramesar, P. A. Singer, and A. S. Daar. 2008. "South Africa: From Species Cradle to Genomic Applications." *Nature Review Genetics* 9: S19–S23.
Hess, C., and E. Ostrom. 2007. "Introduction: An Overview of the Knowledge Commons." In *Understanding Knowledge as a Commons*, edited by C. Hess and E. Ostrom, 3–26. Cambridge, MA: MIT Press.
Johnson, C. N., A. Balmford, B. W. Brook, J. C. Buettel, M. Galetti, L. Guangchun, and J. M. Wilmshurst. 2017. "Biodiversity Losses and Conservation Responses in the Anthropocene." *Science* 356 (6335): 270–275.
Katz, F. 2011. "Proposal for a Microbial Semi-Commons:Perspectives From the International Cooperative Biodiversity Groups." In *Designing the Microbial Research Commons*, edited by P. Uhlir, 129–135. Washington, DC: National Academic Press.
Kuzma, J., F. Gould, Z. Brown, J. Collins, J. Delborne, E. Frow, K. Esvelt, et al. 2017. "A Roadmap for Gene Drives: Using Institutional Analysis and Development to Frame Research Needs and Governance in a Systems Context." *Journal of Responsible Innovation* 5 (sup1): S13–S39.
Lewin, H. A., G. E. Robinson, W. J. Kress, W. J. Baker, J. Coddington, K. A. Crandall, R. Durbin, et al. 2018. "Earth BioGenome Project: Sequencing Life for the Future of Life." *PNAS* 115 (17): 4325–4333.
Lezaun, J., and C. M. Montgomery. 2015. "The Pharmaceutical Commons: Sharing and Exclusion in Global Health Drug Development." *Sci. Technol. Human Values* 40 (1): 3–29.
Lubberink, R., V. Blok, J. Van Ophem, and O. Omta. 2017. "A Framework for Responsible Innovation in the Business Context: Lessons From Responsible-, Social- and Sustainable Innovation." In *Responsible Innovation 3: A European Agenda?*, edited by L. Asveld, R. van Dam-Mieras, T. Swierstra, S. Lavrijssen, K. Linse, and J. van den Hoven, 181–207. Cham: Springer International Publishing AG.
Madison, M. J., B. M. Frischmann, and K. J. Strandburg. 2010. "Constructing Commons in the Cultural Environment." *Cornell Law Review* 95: 657–710.
Marx, V. 2015. "The DNA of a Nation." *Nature* 524: 503–505.
Nobre, C. A., G. Sampaio, L. S. Borma, J. C. Castilla-Rubio, J. S. Silva, and M. Cardoso. 2016. "Land-use and Climate Change Risks in the Amazon and the Need of a Novel Sustainable Development Paradigm." *PNAS* 113 (39): 10759–10768.
Ostrom, E. 1990. *Governing the Commons - The Evolution of Institutions for Collective Action*. Cambridge: Cambridge University Press.
Ostrom, E. 1999. "Coping with the Tragedy of the Commons." Annual Review of Political Science 2: 493–535.
Ostrom, E. 2005. *Understanding Institutional Diversity*. Princeton, NJ: Princeton University Press.
Owen, R., J. Stilgoe, P. Macnaghten, M. Gorman, E. Fisher, and D. Guston. 2013. "A Framework for Responsible Innovation." In *Responsible Innovation: Managing the Responsible Emergence of*

Science and Innovation in Society, edited by R. Owen, J. Bessant, and M. Heintz, 27–50. Chichester: John Wiley & Sons, Ltd.
Oye, K. A., K. Esvelt, E. Appleton, F. Catteruccia, G. Church, T. Kuiken, S. B. Lightfoot, J. McNamara, A. Smidler, and J. P. Collins. 2014. "Regulating Gene Drives." *Science* 345 (6197): 626–628.
Paddon, C. J., and J. D. Keasling. 2014. "Semi-synthetic Artemisinin: a Model for the use of Synthetic Biology in Pharmaceutical Development." *Nature Reviews Microbiology* 12: 355–367.
Pálsson, G., and B. Prainsack. 2011. "Genomic Stuff: Governing the (im)Matter of Life." *International Journal of the Commons* 5 (2): 259–283.
Pietsch, W. 2015. "Aspects of Theory-Ladenness in Data-Intensive Science." *Philosophy of Science* 82 (5): 905–916.
Poteete, A. R., M. A. Janssen, and E. Ostrom. 2010. *Working Together - Collective Action, the Commons, and Multiple Methods in Practice*. Princeton, NJ: Princeton University Press.
Potts, J. 2018. "Governing the Innovation Commons." *Journal of Institutional Economics* 14 (6): 1025–1047.
Rodríguez, A. G., M. Rodrigues, and O. Sotomayor. 2019. *Towards a Sustainable Bioeconomy in Latin America and the Caribbean: Elements for a Regional Vision*. Santiago: Natural Resources and Development series, N°191, Economic Commission for Latin America and the Carribean (ECLAC).
Stilgoe, J., R. Owen, and P. Macnaghten. 2013. "Developing a Framework for Responsible Innovation." *Research Policy* 42 (9): 1568–1580.
Strandburg, K., B. Frischmann, and M. Madison, eds. 2017. *Governing Medical Knowledge Commons*. Cambridge: Cambridge University Press.
The Earth Microbiome Project Consortium. 2017. "A Communal Catalogue Reveals Earth's Multiscale Microbial Diversity." *Nature* 551: 457–465.
Torrance, A. W. 2017. "Better to Give Than to Receive: an Uncommon Commons in Synthetic Biology." In *Governing Medical Knowledge Commons*, edited by B. M. Frischmann, K. J. Strandburg, and M. J. Madison, 192–221. Cambridge: Cambridge University Press.
Uhlir, P. 2011. "Designing the Digital Commons in Microbiology - Moving From Restrictive Dissemination of Publicly Funded Knowledge to Open Knowledge Environments: A Case Study in Microbiology." In *Designing the Microbial Research Commons*, edited by P. Uhlir, 77–90. Washington, DC: The National Academic Press.
van de Poel, I., and J. N. Fahlquist. 2013. "Risk and Responsibility." In *Essentials of Risk Theory*, edited by S. Roeser, R. Hillerbrand, P. Sandin, and M. Peterson, 107–143. Springer.
van den Hoven, J. 2013. "Value Sensitive Design and Responsible Innovation." In *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society*, edited by R. Ower, J. Bessant, and M. Heintz, 75–83. Luxembourg: John Wiley & Sons, Ltd.
van den Hoven, J., K. Jacob, L. Nielsen, F. Roure, L. Rudze, J. Stilgoe, K. Blind, A.-L. Guske, and C. Martinez Riera. 2013. *Options for Strengthening Responsible Research and Innovation - Report of the Expert Group on the State of art in Europe on Responsible Research and Innovation*. Luxembourg: Directorate-General for Research and Innovation Science in Society, European Commission, Publications Office of the European Union.
Varshney, R. K., R. Terauchi, and S. R. McCouch. 2014. "Harvesting the Promising Fruits of Genomics: Applying Genome Sequencing Technologies to Crop Breeding." *PLoS Biology* 12 (6).
von Schomberg, R. 2013. "A Vision of Responsible Research and Innovation." In *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society*, edited by R. Owen, J. Bessant, and M. Heintz, 51–74. London: John Wiley.
Wang, F., and W. Zhang. 2019. "Synthetic Biology: Recent Progress, Biosafety and Biosecurity Concerns, and Possible Solutions." *J. Biosafety and Biosecurity* 1 (1): 22–30.
Williams, M. R., and J. C. Hall. 2015. "Hackerspaces: a Case Study in the Creation and Management of a Common Pool Resource." *Journal of Institutional Economics* 11 (4): 769–781.