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Cyborged ecosystems: Scenario planning and Participatory Technology Assessment of a potentially Rosennean-complex technology

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ABSTRACT

Public involvement in technology policy making is particularly relevant because technological development is now reaching into virtually all planetary systems. The advent of Genetically Modified Organisms (GMO) for human food is particularly controversial, and it also raises questions about related technological-based potential products such as cyborged organisms in general. The research question in the present study is, what are the results of a Participatory Technology Assessment of cyborged ecosystems? The method utilized is Participatory Technology Assessment, implemented through scenario planning. The result of the study was three core themes: superfluous technology, dangerous tampering, and potential public health consequences. Resonances were observed between answers by laypersons and experts, indicating that they recognized the same issues but expressed themselves using different vocabularies and with different levels or types of understanding. Criteria are needed to ensure the public is able to engage in policy decisions that involve Rosennean-complex technologies.

1. Introduction

Public faith in the competence of governmental oversight has been eroding in both the United States (Light, 2006; Ashford, 2007; Lofstedt, 2011) and Europe (Lofstedt et al., 2011). The disenchantment is pervasive, from finance (Jabłecki, 2016) to health care (Curtis and Schulman, 2006; Marlow, 2015). The United States Environmental Protection Agency is a target for those alleging either governmental overreach or unnecessary deregulation (Pugsley, 2012). Genetically modified crops are allegedly variously overregulated (Miller, 2001; Ammann, 2014; DeFrancesco, 2013), in danger of overregulation (Qaim, 2009), or underregulated (Schubert, 2016). If the government is widely believed to be the problem, how can the government ever be the solution?

One possible response to this public disenchantment in government is increased public participation in policy making. Governmental and non-governmental efforts in this regard, such as the Public Understanding of Science (Joly and Kaufmann, 2008), upstream engagement (Heidingsfelder et al., 2015), and Participatory Technology Assessment (Bierwisch et al., 2015; Tavella, 2016), have indicated the oceanic immensity of the subject and the trivial gains to be expected from well-intentioned and competent efforts. The deployment of Participatory Technology Assessment, in particular, has been a slog (Rask, 2013).

Public involvement in technology policy making is particularly relevant because technological development is now reaching into our food sources. The advent of Genetically Modified Organisms (GMO) for human food is itself controversial, and it also raises questions about related technological-based potential products. What about the possibility of cyborged organisms for human food (Saguaro, 2006)? What about the release of a cyborged biotic system from out of the laboratory (e.g., into private agricultural lands)? How should the risk be managed? Does the burden of proof of public safety lie with the advocate, or does the burden of proof of public danger lie with the protestor? Public adjudication of these questions presupposes public understanding of these technologies, and this regression once again illustrates the immensity of the issue.

The research question in the present study is, what are the results of a Participatory Technology Assessment of cyborged ecosystems? The ecosystem question is timely because it resonates with the contemporary Environmental Internet of Things (EIOT, Hart and Martinez, 2015), itself a non-autonomous, evolving

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system of novel risks beyond human control. At the same time it reminds us of earlier attempts at developing biosystems with Artificial Intelligence, or "Ecocyborgs" (Clark and Kok, 1998; Clark, 1999). The notion of synthetic or partially synthetic ecosystems lies at the confluence of a number of independent research threads. Some of these research threads are motivated by practical interests. Life Support Systems (Hendrickx et al., 2006), for example, are a product of the human desire to colonize outer space. Other research threads are motivated by purely scientific, academic interests. Basic research into the synthesis or construction of an artificial ecosystem (Clark, 1999) is of the same genre as basic research into artificial life.

2. Theoretical background

2.1. Participatory Technology Assessment

Participatory Technology Assessment is a method that informs governmental policy making with citizen preferences and values. Participatory Technology Assessments have used scenarios in cases of emerging technologies involving multiple stakeholders (technical and non-technical) and complex technologies (Bierwisch et al., 2015; Tavella, 2016). Scenarios are successful under these conditions because they can show how the future might develop from a given decision. Public involvement is invoked in both expert-based decision making and in participative democratic processes (Lach and Sanford, 2010). In the former, the purpose of public involvement is to develop a scientifically literate public that will accept expert opinions and decisions. In the latter, the purpose is to democratize the decision making process. The two decision making processes differ in important ways, but both seek to increase public understanding and involvement.

Public involvement at the assessment of a technology is sometimes called upstream engagement, but this terminology has critics. The policy of upstream engagement originated in response to the Public Understanding of Science (PUS). The PUS is based on asymmetry between experts and the general public. It has been skeptically critiqued as a deficit model that assumes that the general public are empty vessels "to be educated and informed in order to secure support for innovation and reduce social resistance to technology" (Joly and Kaufmann, 2008: 226).

The newer policy of upstream engagement or public engagement is based on symmetric communication between experts and the general public, and it often involves the construction of hypothetical technological scenarios (Heidingsfelder et al., 2015). This newer policy is particularly relevant to cyborged ecosystems and other potentially Rosennean-complex technologies because it envisions two-way communication at early stages of technology development between experts and the general public. Upstream engagement may be considered as not just a precursor but as a prerequisite to relevant social groups. Upstream engagement has also been criticized as embedded in the "linear model of innovation as a one-way flow from basic research to the users" and as being ineffective against powerful and established technology commercialization interests (Joly and Kaufmann, 2008: 231). In the linear model, innovation is considered to be irreversible: it is out of the question that Genetically Modified Organisms, or nanotechnology, could ever be retired. That means that if the public is consulted after the vested interests have already taken a major decision, then that major decision is considered as irreversible and not up for discussion or reconsideration. In the linear model, the innovation process demonstrates increasing returns on investment, path dependency and lock-in (Arthur, 1989). What may be more commensurate is a type of innovation that engages and transforms a system and its constituents in its totality, as a whole, as well as its parts. This model of innovation is neither linear nor non-linear, but is rooted in Morin's (2007) notion of generalized complexity, discussed below, in which whole-part relationships are considered.

2.2. The public consultation process: context, stakeholders, scenarios and post-scenarios

The co-creation of technology by experts and the general public requires a meeting place and an embedding process to host scenarios. One specific implementation of scenarios is the Shaping Future model (Heidingsfelder et al., 2015). The Shaping Future model was proposed as a scenarios-based tool for public engagement in technology policymaking. The model responds to the European Commission's Responsible Research and Innovation (RRI) Framework, which has the goal of bridging the gap between the scientific community and society at large (EC, 2012). The RRI Framework comprises six keys, which are engagement, gender equality, science education, open access, ethics and governance. The Shaping Future model proposes a process in which researchers and designers pass technology-related theoretical findings and design know-how over to panels of laypersons. These panels of laypersons evaluate the technology in a series of workshops, with the goal of constructing scenarios that can function as starting points for research agendas. The results of these workshops are then passed over to specialists, who convene their own workshops to develop technology roadmaps.

2.3. The research context: cyborged ecosystems and Rosen's concept of complexity

A cyborg is an exogenously extended organizational complex functioning (in the case of an animal, that functioning is automatic or unconscious) as an integrated homeostatic system (Clynes and Kline, 1960: 27). The word cyborg first appeared in 1960, but the cyborg concept arguably owes its existence to the multitudes of soldiers wearing prosthetics returning from World War I battlefields (Borck, 2005; Biro, 2007). The term originally referred to extended humans (Clynes and Kline, 1960). It has since been applied to other species such as insects (Matic et al., 2014; Zhang et al., 2016) and rats (Yu et al., 2016). Cyborging means combining technological and living systems to make a cyborg.

The cyborg under consideration in the present study is the cyborged ecosystem. An ecosystem is an organizational complex of biotic elements and their abiotic environment, putatively functioning as an integrated homeostatic system (Marinakis, 2007). Research specifically on cyborged ecosystems has received only limited attention (Clark and Kok, 1998; Clark, 1999; Vandermeer and Perfecto, 2017). Ecocyborgs are "biosystems of the ecosystem scale that are composed of large sets of both biological and technological components which function in an integrated manner" (Clark, 1999: 120). Applied research in this area is underrepresented. In the Ecocyborg Project, computer models were used to investigate the engineering of large-scale biosystems (ecosystems) combined with Artificial Intelligence control networks (Clark and Kok, 1998; Clark, 1999). The original prototype comprised a physical greenhouse with a system that included sensors, effectors, and controllers connected to computers. Due to lack of funding, further work was limited to computer modelling (Clark, 1999: 41).

The public assessment of cyborged ecosystems is a particularly hard problem because some believe that ecosystems are complex, and others do not. The nature of ecosystems as complex or not will likely impact whether a layperson views cyborging as a threat or not. We do not seek to adjudicate whether ecosystems are complex. We seek to investigate a forum or venue in which members of the public can productively discuss this issue.

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The definition of complexity utilized in the present study is that of Robert Rosen, i.e., Rosennean complexity. Rosen gave characteristics and examples of things that are complex. They possess noncomputable, unformulizable models (Rosen, 2000: 4). They cannot be simulated by finite-state machines, they manifest impredictive loops, and they possess no largest simulable model (Rosen, 2000: 24, 44). “A system is simple if all its models are simulable. A system that is not simple, and that accordingly must have a nonsimulable model, is complex” (Rosen, 2000: 292).

Rosen’s definition of complexity is relevant here because it explicitly includes impredictive loops. If ecosystems are already Rosennean-complex, then cyborging an ecosystem introduces technology into these endless loops. It opens the door to the “ecology of action” by which technology “escapes . . . and enters a set of interactions and multiple feedbacks and then it will find itself derived from its finalities, and sometimes to even go in the opposite sense” (Morin, 2007: 21). The potential for such an effect suggests that there is need to engage society in evaluating, judging, regulating, and acting in transparent processes of participatory assessment.

Understanding where Rosen’s concept came from may help us apply it. Rosen’s model for complexity, which is the topic of this Special Issue, apparently flowed from the work of Hilbert, Gödel and Turing (Rosen, 1991: 305). Rosen himself presented Gödel as an aside, but the linkages between Hilbert, Gödel, Turing, and computability and simulability are stronger than that. In the late Nineteenth Century, mathematician David Hilbert conceptualized mathematics as an axiomatic system comprising meaningless symbols manipulated according to rules. In particular, Hilbert’s second problem asked for a proof that the arithmetic is consistent and free of any internal contradictions. Many believe that Kurt Gödel’s 1931 Incompleteness Theorem showed that Hilbert’s second problem cannot be answered. Gödel’s Incompleteness Theorem states that for any such consistent system of axioms, there will always be statements about the natural numbers that are true but that are unprovable within the system; such a system cannot demonstrate its own consistency (Arana, 2010). In other words, the theory of numbers is not computable or simulable. Turing extended Gödel’s Theorem into an abstract computing machine and applied it to Hilbert’s decision problem. In any case, Rosen’s definition of complexity – non-computable or non-simulable – has deep roots in early twentieth-century mathematics.

Rosen’s definition of complexity is also apparently an abstraction of his views on the question of the definition of life. His interest in the definition of life is self-proved by his own magnum opus (Rosen, 1991). For Rosen, life and complexity were likely the same thing. Life is the apotheosis of non-simulability and non-computability. The question of life was also fashionable in the early twentieth century (Schrödinger, 1943).

Morin sheds light on Rosen’s notion of complexity. Morin’s ideas of order and disorder are useful, as his idea of disorder at first seems to map onto Rosen’s idea of complexity (Morin, 1983: 24):

> “But can we not ask ourselves whether there do not exist, in the real universe, things which are non-algorithmizable, non-reducible, non-unifiable; that is, things which are uncertain, unpredictable, random, disordered, antagonistic?”

Morin asks us to make friends with disorder as it is a necessary companion of order. The two are in constant dialogue. Morin (1983: 34) later clarifies that complexity “involves, among other things, the principled association of two apparently mutually exclusive terms,” e.g., order and disorder. It is here that Morin and Rosen diverge. Rosen’s complexity is Morin’s disorder. The divergence should not be exaggerated. Different labels should not mask the underlying conceptual similarities. Both thinkers also emphasize self-entailment, in one form or another. However, this observation illuminates a point that Morin was trying to make in his distinction between so-called restricted complexity and general complexity. We will shortly return to this point.

Morin’s ideas on order and disorder offer a very different way to think about ecosystems than the thermodynamic formalism, and they are resonant with how semiotics has been treating the subject (e.g., Marinakis, 2012). He talks about how the concept of laws has been replaced by the more general concept of order or “determinations” (constraints, invariances, etc., not to be confused with determinism) (This line of thought is reminiscent of Charles Sanders Peirce’s concept of habit in semiotics.). The particular determinations that exist are said to be contingent on and appropriate to the particular structures (organizations) that exist, and the two co-evolve or co-emerge. In this paradigm, the ecosystem is an organization with co-evolved determinations. Semiotics also embraces this idea, for example in terms of decontextualization: “the real tragedy accompanying the destruction of natural communities is the loss forever of specialized and highly coevolved interactions” (Thompson, 1994: 292; cited in Kull, 1998: 353). These interactions purportedly can be biotic-abiotic, as in ecosystems. Many ecologists are comfortable in calling ecosystems “complex” because the purported age and numerosity of their internal (and external) interactions suggests to them a likely high degree of interrelatedness, with a concomitant peril of interference or substitution. But Morin (2007: 6) calls this only “restricted complexity” because

> “this complexity is restricted to systems which can be considered complex because empirically they are presented in a multiplicity of interrelated processes, interdependent and retroactively associated.”

In other words, the term is anchored to, referenced from, pre-existing notions of what is complex. It is accepted because it is recognizable, relatable to pre-existing ideas, a “hybrid . . . between the principles of traditional science and the advances towards its hereafter” (Morin, 2007: 6). Rosen’s idea of complexity was a subset of restricted complexity, because Morin did not consider non-simulability.

What is complexity that is not anchored in pre-existing notions? Morin (2007: 6) presents “generalized complexity” as opposing three fundamental principles of classical science. Generalized complexity (or complexity) opposes reductionism, and tries to conceive of whole-part mutual implication. Complexity opposes disjunction; it accepts separation but tries to establish relation via autonomous dependence (Morin, 2007). Complexity opposes universal determinism, in favor of a relation between order, disorder and organization.

Our research design resonates with Morin’s part-whole perspective, because the cyborging of a single ecosystem is a model for the cyborging of the natural world. Our scenario seems to be one of general complexity (“all fields”) as the thought experiment intersects ecosystems with the well-being or lack thereof of humans (society in all its dimensions). Our precautionary animus for proposing this study also resonates with Morin’s (2007: 21) assertion that “ . . . from the moment an action enters a given environment, it escapes from the will and intention of that which created it, it enters a set of interactions and multiple feedbacks and then it will find itself derived from its finalities, and sometimes to even go in the opposite sense.” Yet Morin overstates his case when he asserts that complexity remains unknown in biology. If part-whole mutual implication is an aspect of complexity, then complexity studies in biology can be traced through Levins and Lewontin (1985) to Smuts (1926). It cannot be assumed that Rosen was not aware of the work of these influential thinkers.

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3. Methods

The present study investigates the use of scenario planning for empowering the public and disrupting the upstream-downstream perspective (Joly and Kaufmann, 2008). The purpose of the scenario in the present study is to determine whether the benefits and risks of the potentially Rosennean-complex technology could be made understandable to the layperson.

3.1. Scenario planning

Scenario planning is a form of exploration-based learning that generates radical innovation through external search, variation and planned experimentation (Reid and Brentani, 2015: 246). Scenario planning is used either to stimulate thinking, or for explaining or exploring the consequences of some decision (Coates, 2000). Scenario planning is used in New Product Development (NPD) (Noori and Chen, 2003; Schuh et al., 2014; Reid and Brentani, 2015). It is also used in evaluating nationwide technology development options (Ghazinoory and Heydari, 2008; Truffer et al., 2010).

Scenario planning comprises several steps, namely (1) identify and define the universe of concern, (2) define the variables that will be important in shaping that future, (3) identify the themes for scenarios, (4) create the scenarios, (5) write the scenarios, and (6) read, review, and evaluate the scenarios (Coates, 2000). The first five steps will be addressed in the Results section. The sixth step, evaluation, will be addressed in the Discussion section.

Well-written scenarios are stories that are (1) internally consistent, (2) link historical and present events with hypothetical events in the future, (3) carry storylines that can be expressed in simple diagrams, (4) plausible, (5) reflect predetermined elements, and (6) identify signposts or indicators that a given story is occurring (Chermack, 2005; Van der Heijden, 2011; Geum et al., 2014). In the present study, internal consistency (1) was ensured by writing the scenarios utilizing a common technology base (i.e., EIOT, smart cities, etc.) and a common science base (i.e., urban metabolism, etc.). Historical and present technologies were linked to future technologies (2) by assuming that the cyborged ecosystems were the result of technology convergence of historical and present technologies. The simplicity and plausibility of the storylines (3, 4) were ensured by basing the scenarios on natural ecosystem theory. The cyborged ecosystem was the predetermined element (5). The future existence of a specific configuration of a cyborged ecosystem will be a self-proving indicator that the scenario is occurring (6).

The present scenario (Appendix A) is in the category of “Profiles and/or Starter Scenarios” (Miles et al., 2016: 138): “Profiles may be developed that represent end-states of particular interest for those concerned with the focal area” (Id). The purpose is to determine what the resulting scenarios might look like. This category of scenario is used for example where regulatory and other developments might make it possible to exploit the new technologies on a wide scale.

3.2. Why this particular scenario?

This scenario was constructed from technologies that mostly already exist in basic forms, such that their extension and convergence into a more complex form is plausible. At the level of components, electronic plants have already been developed (Stavrinidou et al., 2015). Bacteria have been used to perform computations (Mimee et al., 2015). Organic peptide- and protein-based nanotubes have been developed (Petrov and Audette, 2012). Bacteria-mediated delivery of nanoparticles into cells has been performed (Akin et al., 2007). Chloroplast performance has been enhanced with nanotubes (Giraldo et al., 2014). Carbon nanotubes have been used to deliver DNA into plant cells (Fouad et al., 2008). Moreover, ecosystems are said to have goal functions (Fath et al., 2001). There is a body of theory about ecosystem function and growth (Jørgensen et al., 2000; Fath et al., 2004; Burkhard et al., 2011; Pulselli et al., 2011).

At a larger and more comprehensive system scale, cyborged ecosystems are also a plausible result of the convergence of technologies such as the hypothetical Environmental Internet of Things (EIOT) and smart cities. The EIOT is proposed to have nodes with Internet (or wireless) connectivity, where the sensors on the network are of a wide variety of technologies (Hart and Martinez, 2015). This variety is analogous to the variety of biotic and abiotic components that comprise an ecosystem. Smart cities are proposed to embed Information Technology and to use the collected information liberally for socio-economic development (Allwinkle and Cruickshank, 2011). This approach resonates with the notion of an Ecocyborg (Clark and Kok, 1998; Clark, 1999) as a biosystem having Artificial Intelligence (Information Technology).

This scenario is also useful because it is general enough to represent a variety of ecosystems. It represents a terrestrial ecosystem that is generic enough to be an agricultural field, an urban landscape or a meadow. In summary, the scenario describes the introduction of nanobiotechnology into a terrestrial ecosystem. The technology is placed in soil microorganisms and in plant chloroplasts. Artificial Intelligence is also introduced through neural net-shaped root and below ground fungal systems. Electric plants serve as above ground sensors. The scenario comprises an EIOT extended with Artificial Intelligence (root-fungal neural networks) and nanobiotechnological flora, fungi and microbes.

3.3. Sample and coding

The scenario was given to six management graduate students, interested laypersons all, enrolled in a course on the Management of Technology, and to two resident ecology professors. We used two qualitative research methods (Glaser and Strauss, 2009 [1967; Glaser and Strauss, 2009 [1967]) to capture salient reactions from the observers. We first utilized scenario planning to produce and introduce a cyborged ecosystem scenario to readers, or more technically, observers. Then following Strauss and Corbin (1990) (but see Kendall, 1999), we compared written comments among observers to discover novel insights that emerged between them, rather than forcing comments into pre-ordained concepts and categories, or ‘codes’, that had been a priori derived from existing theory (Glaser and Strauss, 2009). Codes are short-hand labels for distinct concepts identified among prominent adjectives in the written comments. The practice of searching for commonalities in written comments by different people, or ‘axial coding’, is useful when not much is known about a specific social phenomenon (Charmaz, 2000; Hayter, 2005).

4. Results and discussion

As a preliminary matter, the first three steps (Coates, 2000) of scenario planning were addressed (Table 1). These steps were utilized by the researchers to write the cyborged ecosystem scenario.

Scenario evaluation followed these three steps. Scenario evaluation was performed by both the panel of laypersons and by the panel of experts. The laypersons evaluated whether the scenario rendered the technology intelligible. The authors evaluated whether the scenario was an effective tool for facilitating public engagement. Under the Shaping Futures model, the results would be passed over to specialists for use in their own workshops to develop technology roadmaps.

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Table 1
The first three steps in scenario planning and applied to the present study (Coates, 2000).

Step number, and activity within that step	The steps applied to the present study
Step (1): identify and define the universe of concern	Ecosystem structure and function
Step (2): define the variables that will be important in shaping that future	Ecosystem physical variables related to nutrient cycling and energy flow; primary production (vegetative growth)
Step (3): identify the themes for scenarios	The technologicization of the ecosystem; the production of ecosystem services by a natural-synthetic hybrid

There was considerable similarity in the issues raised by the laypersons and the issues raised by the experts. Three core themes emerged: superfluous technology, dangerous tampering, and potential public health consequences. What differed was the vocabulary with which laypersons and the experts related their opinions and concerns.

4.1. Superfluous technology

A common core theme among both laypersons and experts was that ecosystems are already optimized through natural selection, such that the incorporation of nanobiotechnology is superfluous. One layperson wrote *ideally, this project is logical to sustain an ecosystem, however the Earth's processes and natural selection have been doing this for millions of years*; and *this seems like an extremely expensive project for something that nature can already do itself.* The latter statement dovetails with another issue that concerned only laypersons, namely expense. Another layperson wrote *who will be maintaining the human-made technology in the ecosystem?* and more directly *who will be funding this technology?* The apparent superfluidity puzzled one of the laypersons, who wrote *what is the final goal of implementing systems like these?*; and *these cyborged ecosystems seem ideal for use on another planet/moon if the human race were to live somewhere else besides Earth.*

The experts stated their opinions in terms of the thermodynamic view of ecosystems. This view holds that ecosystems are maximizing entropy and destroying free energy (i.e., the principle of maximum energy dissipation, Fath et al., 2001; Chapman et al., 2016). Complex systems, biotic and abiotic, self-organize to produce maximum entropy (Dewar, 2003; Lorenz, 2003), including ecosystems (Jørgensen and Fath, 2004; Yen et al., 2014). One expert noted that *ecosystems are already maximizing entropy and destroying free energy.*

4.2. Dangerous tampering (resilience)

The experts viewed ecosystems as finely tuned thermodynamic engines, such that ecosystem cyborging is a risky enterprise because it would upset those engines. A layperson stated *genetic engineering is always a risky avenue and its results do not always end up as expected.* There were apparent concerns about exposing natural ecosystems to the cyborg. One layperson asked *where will this enhanced ecosystem be placed? Will it have new location or will the enhanced computer plants be placed in with an existing ecosystem?* Another layperson asked *how would other non-cyborged organisms, such as animals, react to this?* One layperson seemed to question the resilience of the cyborged elements. One layperson asked *how durable are these cyborg plants? Can it withstand intense storms or human tampering?*

The experts also viewed tampering through the rubric of resilience. Resilience is thought by some academics to be a goal of ecosystems (Cropp and Gabric, 2002). It is also thought that human intervention may decrease ecosystem resilience (Bertness et al., 2015). One expert asked *how much can ecosystems respond when innovations are introduced into them?* Another asked *does cyborging decrease ecosystem resilience?*

4.3. Potential public health consequences

The laypersons evidenced a concern with the potential public health consequences posed by the cyborged ecosystem. Both the laypersons and experts explicitly and implicitly raised the need of public engagement prior to deployment of the cyborged ecosystem. One layperson asked *what are some potential health consequences of these cyborg plants?* Another asked *would the general public be informed about the possibility of implementing an ecosystem like this before it is just created?*

The experts were also concerned about public health. One asked *what risks do people face when ecosystems get smart and how can scenarios help people understand those risks?* The shift away from ecosystem risk to public health risk could not be clearer.

5. Discussion

The research question in the present study is, what are the results of a Participatory Technology Assessment of cyborged ecosystems? The resonances between answers by laypersons and experts were surprising and unpredicted. The statements of both laypersons and experts could be captured with three core themes: superfluous technology, dangerous tampering, and potential public health consequences. Statements by both laypersons and experts were in each core theme. This means that both laypersons and experts recognized the same issues, even if they expressed themselves using different vocabularies and with different levels or types of understanding.

The laypersons and the experts also both demonstrated the same lack of conceptual clarity regarding Nature. Two of the core themes were not unexpected, namely dangerous tampering, and potential public health consequences. However a third core theme was unexpected, namely superfluous technology, or the sentiment that technology is an unnecessary and inferior addition to Nature. Though natural selection and thermodynamics were invoked as rationale for this core theme, these two natural processes do not produce unimprovable results. Natural selection is a process of continual change. Thermodynamics predicts that living things have the goal of destroying free energy to create entropy (Broda, 2014: 53; Vallino and Algar, 2016). It does not predict that living things evolve dissipative structures to destroy free energy perfectly. Nature may have laws, but even natural laws do not necessarily produce perfection. This core theme may rather reflect a notion of Nature that is an inherited conglomerate, an agglomeration of logically incompatible but historically intelligible belief-patterns. “Nature is perhaps the most complex word in the language” (Williams, 2014: 219). Our contemporary view of nature is both scientific and romantic (Cunningham, 2001: 78–79): scientific as it derives from the secularization of intellectual life led by France in the Eighteenth Century; and romantic as it contemporaneously derives from German Romanticism. Hence we have laws (scientific) of Nature that are allegedly perfect if not Divine (Romantic). Cyborging Nature interferes with those allegedly perfect laws. The significance of this finding is that the conceptual confusion latent in this conglomerate concept of Nature, and the concomitant uncertainty, is stimulating precaution

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in both laypersons and experts. Precaution is a rational response to uncertainty. It is just not clear how much of that uncertainty is rational.

6. Conclusion

Rosen's idea of complexity is a product of his time. In the early Twentieth Century, mathematicians were grappling with computability and simulability, and scientists were musing about life itself. Rosen viewed these as examples of complexity. But if scientists could not understand these things, how could laypersons? Is it possible that laypersons could socially construct a Rosennean-complex technology, a technology too complex for scientists to grasp? As contemporary technologies become more complex and proliferate, the relevance of the question to open society intensifies.

6.1. Implications for practice

A practical contribution of the present study is its demonstration of the use of scenario planning to facilitate the Public Technology Assessment of potentially Rosennean-complex technologies. Future Research. We suggest modifying the scenario planning approach by preceding scenario exercises with educational activities that present all sides of the issues in focus. These activities could include discussions on the Precautionary Principle (Marinakis et al., 2016), or on issues from the perspective of those harvesting the natural resource in questions. Experts would be asked to act as advocates for their positions. Laypersons would likely be more receptive to this method than the experts. A study of public and expert opinion on the various roles that might be played by ecological scientists in the context of contentious natural resources decision making showed that interest groups and the attentive public were more likely than managers and scientists to support an advocacy role for scientists (Lach et al., 2003). There is precedent for this approach. It has been suggested that citizen juries follow and evaluate policy making (Tavella, 2016). Citizen juries have already been proposed as a tool to "overcome the expert/lay divide" (Lach and Sanford, 2010: 131), and their application may well be particularly useful in contentious debates. Following and evaluating are also potentially valuable components, but there is no reason to wait to engage citizens as jurors until the policy has already been made.

6.2. Limitations and future research

The present study comprised only one hypothetical terrestrial ecosystem scenario, one panel of laypersons and two experts. It did not present an actual deployed technology to the panel to compare their perceptions with more widespread public perceptions. Future research can be directed towards investigating criteria that ensure the comprehensibility to the general public of potentially Rosennean-complex technologies. These criteria may include scientific as well as literary guidelines. As mentioned above, future research could also combine advocacy and educational activities with the scenario evaluations.

Appendix A. The scenario exercise follows.

Instructions to Participants

You arebeing asked to participate in a study to determine whether hypothetical scenarios can help make proposed complex future technologies more understandable to the general public. In particular this study seeks to determine whether "Rosennean-complex" technologies can be made more understandable. Something is Rosennean-complex if it is not simulable or computable. Life, for example, and consciousness, are not simulable or computable. Rosennean-complex technologies are technologies that are not simulable or computable.

The following scenario describes a hypothetical ecosystem that is tricked out with Genetically Modified Organisms and Nanotechnology, to seek to maximize its performance. Much of this technology already exists, but not all of it and not in this combination. This ecosystem is an example of a cyborg. A cyborg is an exogenously extended organizational complex functioning (in the case of an animal, that functioning is unconscious) as an integrated homeostatic system.

Your assignment: what questions or concerns, if any, do you have about introducing such a technology into society.

Cyborged ecosystem scenario

The hypothetical cyborged ecosystem is an ecosystem (for example, a forest for timber harvesting, an agricultural field) made of both human-made technology and of nature. An ecosystem is a community of living organisms, in combination with their environment (like air, water and mineral soil), interacting as a system. The cyborged ecosystem uses human-made technology to regulate and supplement nature, with the goal of optimizing ecosystem performance. The cyborged ecosystem contains sensors that measure the solar energy arriving at the ecosystem, and then how that solar energy either flows as heat into the soil or returns back to outer space. Chemical sensors are also placed in the soil to measure soil water and nutrients. Optimal heat, water and nutrients in the cyborged ecosystem are maintained by electronic heaters, water dispensers and chemical dispensers.

All of these sensors are cyborged plants, fungi and bacteria. Above-ground sensing is performed by electronic plants. Below-ground sensing is performed by cyborged below-ground networks formed by cyborged fungi and cyborged plant roots. These networks also act as neural computing nets that learn through accumulated experience, that seek to optimize ecosystem goal functions, and that emulate natural ecosystem function and growth. In other words, the plants are sensors and the roots are computers. Computation is also performed by the soil bacteria and by the plant cells to optimize their own contributions to the ecosystem.

The ecosystem soil is extended with nanotechnology. The soil capillary action is optimized with organic peptide- and protein-based nanotubes. The soil chemistry is optimized with slow-release nanoparticles containing bacterial and fungal spores, and nutrients. If the below-ground networks determine that the soil bacteria are low-performing strains, then the soil is subsequently inoculated with nanobiotechnological bacteria. These are bacteria loaded with organic peptide- and protein-based nanotubes containing innovative synthetic genes that are spread through lateral gene transfer.

When these nanobiotechnological bacteria die and their nanotubes decompose, the decomposed nanotubes are taken up by plant roots. That vegetation may then be consumed by a mammal.

Nanobiotechnological vegetation also grows in the ecosystem, in which the chloroplast (photosynthesis) performance is enhanced with nanotubes and the plant vascular system is optimized with nanotubes. If the vegetation growth is not optimal, new engineered DNA is delivered to the vegetation through nanotube delivery.

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