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The paradox of sustainable innovation: The ‘Eroom’ effect (Moore's law backwards)

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ABSTRACT

Innovation has been widely acknowledged as a key mechanism for addressing sustainable development concerns. However, less attention has focused on downstream commercialization challenges such as achieving increasingly complex and stringent regulatory approval. Such challenges may hinder the development of more sustainable technologies, especially those coming from smaller or publically funded institutes. As well, they may obstruct the development of applications that could provide societal benefits, but may only have limited commercial viability due to small market niches or applicability to customers with limited financial means. We explore this apparent paradox using the concept of the Eroom effect (Moore's Law backwards), i.e. where improved price performance due to technological advances are outweighed by increasing costs of regulatory approval and other commercialization costs. We illustrate this phenomenon with two cases of publically funded institutes, one developing transgenic cotton, and the other lignin transformation technology that can replace petroleum-based feedstocks in a number of industrial applications. We discuss the unintended consequences of the Eroom effect and conclude with implications for industry, policy and NGOs.

1. Introduction

Innovation has been widely acknowledged as a key mechanism for addressing sustainable development concerns (Boons et al., 2013; Hall and Clark, 2003; Hall and Vredenburg, 2003; Hart and Milstein, 1999; Huisingh et al., 2013; Matos and Silvestre, 2013; Silvestre, 2015a). Modern scientific advances, as well as our capabilities in technology management, provide enormous opportunities for improving the sustainability of products and services. For example, improved cost and performance have been recognized as facilitating the widespread diffusion of information technology, resulting in the information age. In 1965 Gordon Moore, a founder of Intel and Fairchild Semiconductor, noted: ‘‘*With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip .... The advantages of integration will bring about a proliferation of electronics, pushing this science into many new areas*.” (Present, 2000, p 82). This improved price-performance phenomenon has since been called Moore's Law, and in gene sequencing a similar phenomenon has been called Carlson's Curve (Economist, 2006). It could thus be argued that the competencies and lab costs of developing many technologies should be decreasing with time, given that we have greater knowledge with which to build on, and a greater pool of trained scientists and engineers (Hall, 2016). Mobilizing such capabilities towards sustainability concerns can thus be a major driver of improved social and environmental impacts.

According to Montalvo and Koops (2011), there are a wide range of market and policy factors that drive more sustainable innovations, which in turn are shaped by for example ethical, environmental, health & safety and cost factors. By more sustainable, we mean innovations that have better environmental and social performance characteristics over incumbent products or services. Such innovations are typically developed through R&D labs in corporations, universities and government institutes (Hall et al., 2014a; Wagner et al., 2014). However, while the role of such market and policy factors have been well recognized within the literature, less attention has focused on some of the key challenges of moving promising eco-innovations ‘off the shelf’ (Hall et al., 2014b), and specifically the barriers of meeting highly complex and increasingly stringent regulatory approval processes. For example, public concerns over emerging technologies, such as transgenic technology in agriculture, heightened by for example non-governmental organizations (NGO) and other public pressures, have resulted in major costs induced by regulation that now often outweigh the actual scientific lab costs. As a result, only a few large multinational corporations have adequate resources to bring new transgenic crop varieties to the market, and even then they are unlikely to be viable unless only one is competing in the segment. Furthermore, in addition to monopolistic tendencies, high regulatory barriers may also make it difficult for smaller organizations and public sector institutes to compete. These latter organizations often have a mandate to develop technologies that provide societal benefits, but may otherwise have limited commercial viability, due to small market niches or applicability to customers with limited financial means (Manjunatha et al., 2015).

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In this paper we explore this apparent paradox, i.e. improved price-performance characteristics analogous to Moore's Law, versus the actual costs of regulatory approval and other commercialization costs, and how this may hinder sustainable innovation. Drawing on data from the pharmaceutical industry, Scannell et al. (2012, p 191) have framed this paradox as "Eroom's Effect", i.e. Moore's Law spelled backwards, noting that "*R&D efficiency, measured simply in terms of the number of new drugs brought to market by the global biotechnology and pharmaceutical industries per billion US dollars of R&D spending, has declined fairly steadily.*" Among other issues specific to the pharmaceutical industry, they note that regulators have become increasingly cautious, gradually reducing their risk tolerances to avoid safety disasters such as the drug Thalidomide, the anti-morning sickness treatment for pregnant women that resulted in birth defects. They further note that some corporations have increased their R&D resources to gain first mover advantage and create high barriers to entry.

We specifically explore the implications of the Eroom effect on public institutions such as university and government labs attempting to develop more sustainable technologies. To do so we investigate two cases. The first is a Brazilian public research institute, the Brazilian Agricultural Research Corporation (EMBRAPA) attempting to develop transgenic cotton to deal with a devastating pest infestation that avoids pesticide use. The developers believe the technology is thus likely to be more sustainable because it uses less inputs such as insecticides and herbicides, and the fuel consumption is substantially reduced because less spraying operations are needed. Although technologically feasible, the institute recognizes that gaining regulatory approval for this product may be beyond their resources or may take too long for reasonable impact. As a result there are concerns about commercial viability, and whether the potential societal benefits will be undermined by regulatory barriers, which in turn have been shaped by anti-GMO activism.

The second case draws on a Canadian university's attempts to develop renewable lignin-based products based on new biodegradation technology that can be used to replace non-renewable petroleum feed stocks in various industrial settings, such as food flavoring (e.g. vanilla), and carbon fibers that can be used for automotive, electronics, energy and defense applications. For food additives, a key attribute is whether the technology can be framed as a natural ingredient, otherwise it cannot compete against the synthetic, low cost guaiacol-based vanilla. Carbon fiber applications are highly dependent on the industry application, where for example regulatory approval in defense and aerospace applications are substantially higher than for example in consumer electronics.

We contribute by providing a greater understanding of the challenges associated with technology development that improves ecological and societal sustainability, specifically regarding the downstream costs that are often overlooked by those developing the technology. We argue that technological innovations are increasingly being hindered by complex and often prohibitive downstream costs such as regulatory approvals, labelling and trade policies. We discuss the unintended consequences of the Eroom effect and how social and environmental benefits can be used to overcome some of these challenges. More specifically, we propose that advocacy groups, which have played an important role in increasing regulatory standards, could differentiate their opposition to new technologies, for example by providing support for institutions developing technologies primarily for environmental and societal benefit. We also provide recommendations for how regulations can be reformed to avoid discouraging sustainable technology development.

In the next section we discuss the literature on innovation as a panacea for sustainable development, and how Moore's Law and related concepts have been used to illustrate major advancements in technology and the proliferation of new industrial structures. We then discuss how relatively new non-technological Eroom hurdles, such as increased regulatory constraints and heightened concerns from NGOs and civil society, have in some cases negated the promise of improved price-performance.

2. The innovation and entrepreneurship panacea for sustainable development

Seminal studies, particularly those published in practitioner business journals, have identified innovation, the introduction of new products, services, means of transportation, sources of raw materials or new organizational structures (Schumpeter, 1942), as a panacea for sustainable development concerns. For example, the much cited (Porter and Van der Linde, 1995, p 120) paper argues that companies "… *are constantly finding innovative solutions to pressures of all sorts—from competitors, customers, and regulators. Properly designed environmental standards can trigger innovations that lower the total cost of a product or improve its value. Such innovations allow companies to use a range of inputs more productively—from raw materials to energy to labor—thus offsetting the costs of improving environmental impact and ending the stalemate.*"

Whereas Porter and Van der Linde focus primarily on environmental impacts in modern industrial settings, Hart and Milstein (1999) broaden the panacea perspective by emphasizing that environmental issues are closely connected, and thus correlated to, economic and societal concerns, and that a global perspective is needed. Drawing on Schumpeter, they argue that sustainability concerns are creating a new round of creative destruction, where incumbent non-sustainable technologies will be obsolete, providing "unprecedented opportunities" for businesses developing new sustainable technologies and business models, and by exploiting untapped developing and emerging markets (London and Hart, 2004). New entrants often drive creative destruction at the expense of incumbent firms.

The allure of innovation has been encapsulated in the above discussed Moore's Law and Carlson's Curve, which essentially illustrates how new technologies can drive down prices and increase performance. This appears to have happened in for example much of the electronics industry (Eizenberg, 2014). According to Fichman et al. (2014, p 333), "*The main implication of Moore's Law is to rapidly increase the range of what is technically and economically feasible to accomplish with IT. It explains why IT has become the dominant enabling force for both product and process innovations today. In fact, Moore's Law can be seen as a fundamental enabler of many instances of disruptive innovation (Christensen, 1997) and creative destruction (Schumpeter, 1950).*" In theory, the dynamics of technological innovation could thus foster more sustainable technologies that will eventually become more economically competitive over the current, less sustainable, incumbents.

A wealth of studies have since focused on sustainable development innovation and entrepreneurship. For example, Hojnik and Ruzzier's (2016) literature review found 155 journal articles published between 2000 and 2015 on eco-innovation. A number of special issues have also focused on the topic, including numerous special issues in the *Journal of Cleaner Production* (Boons et al., 2013; Charmondusit et al., 2016; Hall and Clark, 2003) as well as innovation and entrepreneurship journals such as *Research Policy* (Markard et al., 2012; Smith et al., 2010); *Technovation* (Hall, 2014); *Journal of Engineering and Technology Management* (Wagner et al., 2014); and *Journal of Business Venturing* (Hall et al., 2010) to name a few. The underlying logic of these studies is based on the assumption that innovation is a much more appealing and politically feasible mechanism when compared to alternatives such as population control, reducing economic growth or the lowering of living standards. According to Nidumolu et al. (2009, p 57) "*There's no alternative to sustainable development*".

To date empirical evidence supporting the innovation panacea argument has however been mixed. For example, Vivanco et al. (2015) concluded that many eco-innovations actually increased pressures on the environment, due to various forms of rebound effects. For example, greater engine efficiency may encourage motorists to drive more, resulting in an overall increase in environmental impacts. Further, Ambec et al. (2013)'s summary of empirical studies on the Porter Hypothesis found that while strict regulations stimulated innovation and thus improved environmental performance, there was less evidence that it enhanced business performance. They argue that one reason could be the lack of appropriate data used to test how regulation leads to innovation. They further note that the conflicting empirical results for the Porter Hypothesis is that "*firm, industry, or environmental characteristics may affect the extent to which innovation offsets and productivity or competitiveness enhancements occur*" (p 16). More recently Marin and Lotti (2016, p 22) similarly found that environmental innovations differ from other innovations regarding firm productivity, and specifically found that they typically offer a lower return when compared to non-environmental innovations, "*especially so when considering those with a public nature …*". They further argue that, coupled with the limited availability of financial resources for R&D, environmental innovations may be 'crowded out' by non-environmental ones, particularly in the short term. França et al. (2017, p 155) similarly argue, "*Typically, the business case of sustainability is not understood profoundly enough; the planning horizon and system scope are insufficient; the competence to bring together people into systematic ventures towards sustainable business is too low*."

Two main themes have emerged from these studies and other recent literature reviews (Loiseau et al., 2016; Bossle et al., 2016) and empirical studies (e.g. Horbach, 2016). First, all emphasize the importance of industrial and national contexts, and call for more research to address these differences and related specificities (e.g., Przychodzen and Przychodzen, 2015; Cheng et al., 2014). Silvestre (2014) for example, investigates the effectiveness of cleaner production innovations in the mining industry of an underdeveloped area in Brazil, highlighting the importance of strategic managerial and policy orientation towards sustainable development that needs to complement technological innovation. Silvestre (2015b) underlines the special situation in many developing and emerging countries where high levels of complexities and uncertainties represent additional barriers to sustainable development. Second, all studies recognize that regulations are crucial, and in some cases the most important driver of eco-innovation. Recently, Huang et al. (2016) have found for the case of manufacturing plants in central China that regulatory pressure has a distinct positive impact on green innovation performance. Similarly, Cai & Zhou (2014) state that environmental regulations lead to eco-innovation, while they highlight the reinforcing effect of organizational and technological capabilities as well as corporate social responsibility. However, much less emphasis is placed on how the regulatory approval process, and specifically obtaining regulatory approval for new technologies, affect more sustainable innovations. As we show below, even though government policies in numerous countries are actively encouraging the development of more sustainable technologies, or actively discouraging unsustainable practices through regulations (*c.f.* Calvo et al., 2015; García-Á lvarez et al., 2015; Hunt and Fund, 2016), paradoxically regulatory hurdles appear to be hindering these efforts, especially for smaller organizations and publicly funded labs. This exacerbates the situation of small and medium sized enterprises who have been repeatedly found to lag, in terms of their capabilities and inclination towards implementing sustainability innovations (Przychodzen and Przychodzen, 2015; Sáez-Martínez et al., 2016; Silvestre, 2014).

3. The impact of regulations on established versus new entrants

According to Pigou (1932), regulations are developed in response to public demand for inefficient or inequitable market practices, with the intent of benefitting society as a whole rather than any particular vested interest. For example, Stigler (1975, p 140), argues that the theory of economic regulation "*tells us to look, as precisely and carefully as we can, at who gains and who loses, and how much, when we seek to explain a regulatory policy*".

According to Carpenter (2004), capture theory of regulation attempts to explain if, and why government regulation appears to favor larger, older producers and impedes smaller new entrants, where the former use regulation as entry barriers or utilize regulations to impose disproportionate costs on newer or smaller competitors. Reasons he provides for this advantage include the following. First, firms that are better known to the regulator because for example they market more products, will be seen as less uncertain, and as a result typically receive quicker decisions. Second, larger firms are often able to enter market niches earlier, particularly in areas of interest to policy-makers under pressure from organized consumers, such as AIDS sufferers. Third, larger firms usually benefit when regulators are unlikely to make immediate approval decisions, because they can more easily absorb the costs of delays, whereas one delay could cripple a smaller firm. Interestingly, Carpenter (2004, p 614) notes that "*… the advantage of familiarity holds even in cases where the familiar firm has a bad reputation for product safety*".

While capture theory helps explain why large incumbents have an inherent advantage over new entrants, the apparent paradox of regulations – as a driver of more sustainable technologies but also a mechanism that may hinder new entrants – can be framed using the Eroom effect. Scannell et al. (2012, p 191) found that, contrary to what would be expected by Moore's Law, "*R&D efficiency, measured simply in terms of the number of new drugs brought to market by the global biotechnology and pharmaceutical industries per billion US dollars of R&D spending, has declined fairly steadily*."

They argue that the cause of the Eroom effect is due to the following. First is what they call the 'better than the Beatles' problem analogy, where it is difficult to achieve commercial success shortly after a for example highly successful new pharmaceutical product (or song) has been introduced. "*An ever-improving back catalogue of approved medicines increases the complexity of the development process for new drugs, and raises the evidential hurdles for approval, adoption and reimbursement. It deters R&D in some areas, crowds R&D activity into hard-to-treat diseases and reduces the economic value of as-yet-undiscovered drugs. The problem is progressive and intractable*" (Scannell et al., 2012, p 193). Although they acknowledge that this may be a specific problem to the pharmaceutical industry, we propose that the 'better than the Beetles' problem may discourage competing products in any industry with high regulatory hurdles.

The second is the 'cautious regulator' problem, where lowering of risk tolerances of regulatory agencies raises the bar for new products. Scannell at al. (2012, p 194) argue that over the years regulators have tightened regulations in response to *"… real or perceived* sin *by the industry, or genuine drug misfortune*", such as Thalidomide. Although increased regulatory standards are obviously appropriate and socially responsible, they also note that it has had important competitive implications, where "*… most of the past 60 years large and sophisticated drug companies may not have been disappointed to see the regulatory ratchet tighten because it reduced competition*" (Scannell et al., 2012, p 194).

The other two causes of the Eroom effect are the ‘throw money at it’ tendency, where additional human and other resources are allocated to R&D, and the ‘basic research–brute force' bias. Scannell et al. (2012) argue that for the former, strong returns on R&D investment in the past, plus a relatively poor understanding of the stochastic innovation process and the importance of being first to market has contributed to the rise in R&D spending in major pharmaceutical companies. Similarly, the ‘basic research–brute force’ bias is the tendency for firms to overestimate the ability of advances in basic research and forced screening methods to increase the probability that for example a molecule will be safe and effective in clinical trials.

We argue that an Eroom effect may be hindering the development of publically funded R&D efforts for more sustainable technologies. Increased regulatory costs and complexities require specialized competencies and resources that are usually beyond the reach of most government and university labs. Such resource requirements compound the challenges of relatively lower rates of return for environmental innovations focused on a public good, as outlined by Marin and Lotti (2016) above. Furthermore, we add to Scannell et al.'s (2012) study that regulatory hurdles have been heavily shaped by NGO campaigns and public controversies in for example nuclear power, agricultural biotechnology and non-conventional oil and gas such as hydraulic fracturing, oil sands extraction and ultra-deep offshore petroleum development (Hall et al., 2014c). The end result is that the Eroom effect, and specifically regulations and NGO advocacy pressure, may have paradoxically resulted in overwhelming challenges for publically funded sustainable technology development.

3.1. Good intentions resulting in unanticipated outcomes

Before we ‘throw the regulatory baby out with the bathwater’, we remind the reader that increased regulatory costs and approval times are driven by, among other things, improved health and safety standards, which in turn were developed to rectify market failures and avoid tragic consequences of economic activities. Similarly NGO pressures have also played a major role in generating awareness for sustainability issues. Putting aside for now Porter and Van der Linde's (1995) efficacy concerns over “properly designed environmental standards”, we assume for now that the Eroom effects are the result of unanticipated regulatory and NGO pressures but with good intentions.

Unintended consequences are common phenomena in new technology development. For example, Nelson and Winter (1982) have noted that innovation resolves some problems but also creates new, unanticipated ones that must then be later addressed. There is also a stream of research in political science that focuses on the unanticipated outcomes (see Perri 6, 2014 for a review), much of which has been influenced by Merton (1936). He argued that possible causes of unanticipated consequences include ignorance; errors in problem analysis or the “*too ready assumption that actions which have worked in the past led to desired outcome will continue to do so”* (p. 901); when foreseen immediate interests override long-term interests; when basic values prohibiting certain actions may result in unfavorable long-term results; and finally the anticipation that some consequence may happen causes people to find solutions before the problem occurs.

Some contemporary examples of the anticipation factor is the heightened fears of the health, environmental and social (e.g. farmers' rights) impacts of transgenic crops (e.g. Hall and Martin, 2005; Herring, 2007), resulting in strict regulatory approval processes (Hall et al., 2008). For example, Hall et al. (2014a) found that Monsanto's transgenic soybeans encountered major opposition in Brazil, resulting in significant delays before the National Congress approved their planting. They also argue that Monsanto's participation in transgenic Golden Rice, a publically supported technology with a primarily social proposition to improve nutrition in poor regions was marred by NGO opposition, resulting in the technology's deferment.

4. Methodology

Following Eisenhardt (1989), Gephart (2004) and Siggelkow (2007), we extend the theories of regulation and the innovation literature by analyzing the effects of regulatory complexities on the development of more sustainable technologies funded by publically funded institutions. We selected two instrumental cases in response to calls to address national and industry related specificities (Przychodzen and Przychodzen, 2015; Cheng et al., 2014), drawing on an emerging economy (Brazil) and a developed economy (Canada) developing technologies in various industrial contexts (agriculture, food additives and carbon fibers for automotive, aerospace and defense applications).

The first case involves a Brazilian public research institute, the Brazilian Agricultural Research Corporation (Embrapa) attempting to develop transgenic cotton for reducing environment impacts in large scale farming in the short term, and then to benefit small farmers in a later stage. As such, the developers believe the technology is more sustainable than alternatives. Embrapa is a governmental research institute affiliated to the Brazilian Ministry of Agriculture with the mandate of *"develop research, development and innovation solutions for the sustainability of agriculture, for the benefit of Brazilian society"* (Embrapa, 2016). Founded in 1973, Embrapa's research has profoundly influenced the country's agriculture sector by for example quadrupling the beef and pork supply, increasing the poultry supply 22-fold, and converting large unproductive tracts of land into the country's source of nearly 50% of today's grain production (Embrapa, 2016). Embrapa's research is conducted with the cooperation of other state, public and private organizations such as universities, companies and foundations. They employ 2444 researchers, of which most have PhD or post-doctoral degrees from universities in Brazil and abroad.

A significant area of Embrapa's research is focused on genetic engineering seeking to improve productivity and add value to Brazilian agriculture. However, while their technological hurdles are low, overcoming regulatory challenges may be beyond their capabilities and available resources, and as a result may take too long for reasonable impact. We use this case to discuss concerns over commercial viability within these markets, and whether regulatory barriers that may have been shaped by anti-GMO activism will undermine the societal benefits. Data sources include information from peer-reviewed studies, organizations' website and reports. Primary data includes 16 interviews conducted with Embrapa's transgenic crop science team, and observations from numerous site visits by two of the authors of this paper over the course of 10 years.

The second case relates to a publicly funded Canadian university research project aiming to develop lignin-based products based on new biodegradation technology that can be used to replace petroleum feed stocks. The developers believe the technology is likely to be more sustainable than incumbent petroleum alternatives because it is renewable and will likely produce less CO_2 emissions. The technology can be applied in various industrial settings, such as forest products, chemical products and energy, and which in turn may affect several others (e.g., automotive, food processing, construction and aerospace). The research was funded by Genome Canada, a not-for-profit organization that has invested over $1 billion for supporting large-scale genomics research in Canada, primarily through universities. They emphasize that all funded research needs to demonstrate benefits to Canada, and as a result include a social science component, where genomics-related ethical, environmental, economic, legal and social issues (‘GE^{3}LS’) are taken into consideration. This policy was based on the recognition that the linear “technology push” model failed to ensure technology diffusion (Hall et al., 2014a, 2014b).

Data from this case is part of a broader research program aiming to identify technological, commercial, organizational and societal hurdles and levers of the new lignin-based technology platform developed by the scientists (Hall et al., 2014a, 2014b, 2011). In total 80 interviews were conducted with several stakeholders such as managers, NGOs, scientists, trade organization representatives and government officials. Within this platform, we selected lignin-based vanillin and carbon-fiber, as there are complex and expensive regulatory hurdles that need to be overcome before these technologies can be commercialized. For vanillin, we discuss and analyze how the ‘natural’ food market may represent an opportunity, given its high market price when compared to synthetic vanillin. However, getting approval for a new product labeled as natural can be time-consuming and expensive, representing a significant challenge for publically funded institutions.

Lignin-based carbon fiber production is currently one of the most technically challenging applications within the platform of possible products, but potentially one of the most commercially rewarding. For example, according to Chen (2014), the price of lignin burned as fuel after recovery is estimated at $400 *per* ton, while lignin-based carbon fiber is estimated to start at $21,700 *per* ton, and can be worth substantially more, depending on the application. The overall size of the carbon fiber precursor market is estimated at $2.25 billion (Chen, 2014).

Like the other cases, the research is driven by potential environmental benefits. This includes using carbon-fibers to lighten vehicles, reduce fuel and emissions, as well as improve environmental production characteristics over incumbent feedstocks, such as reduced greenhouse gas and toxic gas emissions, by having a shorter oxidation stage, a key to carbon fiber production (Baker and Rials, 2013). However, the industry is under complex and stringent international trade regulations, depending on its application (e.g. aerospace and defense), which is often beyond the capabilities and resources of publicly funded organizations.

5. Transgenic cotton technology

Cotton has been produced in Brazil before European colonization, and increased significantly during the American Civil War, when prices became very attractive. Throughout the twentieth century, cotton became the most important cash crop, particularly in semiarid regions of Brazil, where there were few other agricultural options suited for this environment (Rodrigues, 2015). In the 1980s, production in Brazil was devastated by the boll weevil insect (*Anthonomus grandis*). Since then, cotton farmers abandoned the crop because controlling the insect was infeasible, collapsing the economies of many communities. Brazil, originally 5th in the world for cotton production and a major exporter, suddenly became one of the largest importers.

Managing boll weevil in Brazil became a challenge that was only overcome through sophisticated technologies and large scale farming. This pest prevented small farmers from exploiting this important cash crop, and its management also has significant environmental impacts. For example, according to Embrapa scientists, boll weevil pest control requires multiple spraying with insecticides, which in turn cause ecological disturbances that amplify the difficulties to control several other pests that in other circumstances would not be a significant problem. The pest also requires additional procedures in order to remove any living plant after harvest, and requires expensive monitoring throughout the year along roads, farms, and processing facilities. Note that Brazil is the only major cotton producer fighting boll weevil; the U.S eradicated the insect, and the pest is absent in Asia, Africa, Oceania and Europe, so there are limited opportunities for international collaboration.

Embrapa is developing a transgenic cotton plant to resist boll weevil without the use of insecticides. This plant is expected to reduce production costs and environmental impacts by reducing insecticides used against the targeted pest, and allows ecological equilibrium to help reduce the pressure from other insects. However, developing a transgenic plant requires long-term commitments and multidisciplinary teams. To date many transgenic cotton plants have been commercialized, but they target different pests (e.g. Lepidopters alias butterflies and moths) that usually attack leaves. Boll weevil belongs to a different group (Colleopters alias bugs), and they feed only on reproductive structures. Initial results using a gene from a bacteria (*Bacillus thuringiensis*) proved to be effective against boll weevil (Silva et al., 2016).

After proof of concept, a government sponsored consortium composed of private and government research institutions and the national cotton producers association was created. More recently Embrapa has been collaborating with the Mato Grosso Institute of Cotton Production, where the former was primarily responsible for upstream research and the latter shared responsibilities of downstream development activities such as field tests, regulatory testing and registration.

According to Embrapa documentation provided by one of their crop scientists interviewed in 2015, it takes about three years for gene discovery[1] and three years of proof of concept, for a total of six years of upstream activities, whereas approval could take an additional ten years (Table 1). According to McDougall's (2011) study on the cost and time involved in developing transgenic technology, downstream activities included three overlapping phases: advanced development, pre-commercialization and product launch. Subcategories include production and selection of genetic events (two years), field testing (eight years), regulatory testing (eight years), and finally preparation, submission for commercial planting and submission of documentation for commercial planting in different countries (four years). In total, all activities are estimated to take a total of 16 years, with almost double (ten versus six years) for downstream activities. Perhaps more telling is the estimated costs of these phases (Table 1), where downstream costs are higher than the upstream research costs.

Although we do not have access to longitudinal cost data, Embrapa scientists informed us that gene discovery, once the key challenge to transgenic technology, appears to have become easier, similar to a Moore's Law/Carlson Curve trajectory, albeit more of a normal rather than log function. They however found that downstream development costs remained high, and may even increase, partly because opposition to transgenic technology has been so controversial. For example, one crop scientist interviewed in 2015 stated: *“In the past, I guess ten years ago, we had a situation ... in Brasília, we are in the laboratory and the movement organized by Greenpeace entered the laboratory and broke everything ... and we were very afraid”.* Greenpeace and other NGOs have consistently been opposed to transgenic technology in Brazil, claiming among other things that concentrated farming practices resulted in major environmental impacts and forced small-scale farmers off the land (Hall et al., 2008).

While the commercial drivers of large scale farming are relatively clear and obvious, the commercial viability for small scale, poor farmers is less clear, as they are widely dispersed and typically do not have access to financial mechanisms common in large agri-busi-

[1] Here, “gene discovery” is the simplified terminology commonly used within the field that includes testing the effect of several species, including races of bacteria and testing several combinations of the different components that need to be together in order to make the gene with the function that is being searched. It is thus not restricted to discovering a new gene that was not used before.

Table 1
Average time and costs involved in the development of transgenic cotton trait.
Source: Adapted from McDougall (2011).

Upstream Research Costs			Downstream Development Costs		
	Estimated years	Estimated costs ($US millions)		Estimated years	Estimated costs ($US millions)
Gene discovery	3	17.6	Genetic events production & selection	2	13.6
Proof of concept	3	41.7	Field testing	8	28.0
			Regulatory testing	8	17.9
			Submission for commercial planting (domestic and int.)	4	17.2
Total		**59.3**			**76.7**

nesses. Embrapa scientists lamented that the onerous and expensive regulatory approval process would make this socially beneficial but financially modest technology infeasible. According to one scientist: *"It's very stressful to work with this. While we thought the whole problem was defining the methodology … the problem comes after; I may be dead before I see some of these technologies reach the market."*

6. Lignin transformation technologies

6.1. The new lignin-based vanillin

Scientists at the University of British Columbia, Canada have developed an innovative biocatalysts process that produces vanillin from lignin, discovered serendipitously as part of a larger research project aiming to explore new sustainable opportunities from lignocellulose-derived products. Biocatalysis is the use of enzymes and cells to chemically transform organic substrates into desired products. Such processes are of increasing importance in a variety of sectors due to their advantages of selectivity and more sustainable characteristics over incumbent petroleum-based aromatic compounds. Such compounds can be used as feedstocks to produce a wide range of commercially useful chemicals, such as solvents, detergents, flavors and adhesives. Some aromatic compounds derived through bacterial transformation of lignin include vanillin, used for flavor, and various phenols used in the production of drugs, herbicides, and synthetic resins. The proposed new biocatalysts process to produce vanillin uses a mutant strain of the Rhodococcus jostii bacteria (RHA1) engineered through gene knockout technique to accumulate vanillin and byproducts such as ferulic acid (Sainsbury et al., 2013).

Market prices for vanillin vary significantly, depending on the source of raw material and process characteristics. For example, prices of synthetic vanillin produced from petroleum range between $12–15/kg, lignin synthetic process ranges around $13–17/kg, vanillin from natural rice bran fermentation can cost up to $700/kg and from vanillin beans prices range between $1200–4000/kg (Hall et al., 2014b; Wong, 2012). The estimated initial price of the new RHA1 vanillin is approximately $912/kg, which is based on data derived from the proof of concept stage and before any production optimization efforts have been made, such as improving yield and fermentation time, etc. (Matos and Petrov, 2015). A key hurdle is thus whether the new vanillin can be qualified as 'natural' by regulators, and whether it can compete other types of vanillin, for example the rice bran-based vanillin market (Hall et al., 2014a). According to (Negowetti, 2014), the food industry's marketing of natural products has been very successful, and in 2011 the term 'all-natural' was the second-most-used claim on new American food products. In 2009, sales of products with a 'natural' claim reached $22 billion, and surveys have found that the '100% natural' claim is the most popular among consumers at 31%, followed by the term 'all natural ingredients' at 25% (Negowetti, 2014).

A preliminary assessment conducted by the Canadian Food Inspection Agency (CFIA) on the natural status of RHA vanillin found that it does not qualify as natural, as the current proof of concept process utilizes chemicals such as toluene as a solvent substance to separate vanillin from other byproducts. However, the CFIA expert suggested that changes in the process could lead to approval for a 'natural flavour' label, as stated below:

> "*The production of vanillin from wheat straw using bacteria fermentation would not be considered natural as it utilizes chemicals in the process. The process affects the natural character of the food with a maximum chemical change. […] once the method for extraction/purification of the vanillin into an actual flavour has been explored/established, feel free to contact us again. Under the "Nature, Natural" section of the Guide to Food Labelling and Advertising, there is a small section regarding "flavour descriptors". The information in that section could still apply to your product*." (CFIA Chemistry Specialist, January 2014)

In general, a product is not qualified as 'natural' when manufactured by processing means that changes its naturally occurring state. However, there are ambiguities related to what the term 'natural' means among different countries, which may represent an opportunity to label RHA vanillin as natural in some jurisdictions but not in others. Natural labels vary and include 'Natural' (Canada), 'Natural Flavour' (Canada, USA, EU and Australia) and 'Nature-Identical' (EU and Australia). The CFIA uses two processing standards to help define 'natural' and 'unnatural'. The former relates to food created through processing that has a minimum alteration effect ('natural' food), and the latter relates to food created through processing that has a maximum alteration (CFIA, 2017). Like the standards developed by Canada, the U.K.'s definition of 'natural' refers to the use of specific food processes that involve traditional methods and cooking processes such as baking, roasting or blanching, natural fermentation, dehydration, physical sieving, washing with water, etc. (Food Standards Agency, 2008).

In the U.S., the definition of natural is somewhat informal and defined differently within organizations with the mandate to protect consumer interests. For example, the Food and Drug Administration (FDA)'s policy suggests that natural relates to "*nothing artificial or synthetic (including colors regardless of source) is included in, or has been added to, the product that would not normally be expected to be there*." (FDA, 2016). Such a definition does not consider processing effects and other recent food technology advances that may affect the 'natural' qualification of the food.

On the other hand, the U.S. Department of Agriculture (USDA)'s policy considers issues of processing when defining natural as "*not containing any artificial flavor or flavoring, coloring ingredient, or chemical preservative (as defined in 21 CFR 101.22), or any other artificial or synthetic ingredient",* (USDA, 2005, p 107). Both U.S. agencies have yet to formalize a definition of natural, claiming that it is too challenging, there is a lack of resources and more importantly, there is a lack of evidence that consumers are being misled (Prochnow, 2011). Conversely, consumer advocacy groups are concerned that lack of clear regulation will lead to synthetic vanillin (no use of a vanilla bean source) with 'natural' labels and other NGOs have promoted the view that synthetic vanillin is also a threat to small farmers' businesses (Quartz, 2016; Friends of the Earth, 2014).

Such perspectives represent a paradox in food innovation and safety. On the one hand, the food industry has recognized that, to avoid marketing difficulties, it is important to implement effective product identification regulations that consumers trust (Levidow et al., 2013), on the other hand such systems may hinder the development and identification of new and safe food. For example, as consumer preferences supposedly drive food innovation, the food industry has created technological innovation that promise to be safe without compromising the natural quality of the product, yet 'naturalness' claims have been expensive and difficult to justify and to verify (Avermaete et al., 2003; Levidow et al., 2013).

6.2. Lignin-based carbon fibers

Carbon fibers are currently manufactured from polyacrylonitrile (PAN) precursors, while small amounts are derived from petroleum-based pitches. Due to the high cost of these petroleum-based precursors and their associated processing costs, carbon fiber remains a specialty product limited to aviation, high-end sporting goods, automobiles and special industrial applications such as windmill turbine blades (Baker et al., 2013; Huang, 2009). Lignin-based carbon fiber is an example of process innovation where the new technology is set to improve supply chain productivity, enable new products or enhance cost and performance (Maine et al., 2012). R&D on low-cost carbon fiber manufacturing have been limited to a small number of organizations able to cope with the magnitude of equipment, expertise and access to R&D funding. In order to address such difficulties, research consortia such as Oak Ridge Carbon Fibre Composites was established to promote the development of low cost carbon fiber composite materials. It has over 50 members that represent the entire carbon fiber value chain, from raw materials to downstream applications.

We found that one of the key regulatory barriers for developing new carbon fiber relates to the complexity of U.S. export control policies. Such controls, which are used by European countries, China, Japan and Korea among others, were designed with the purpose of avoiding the spread of weapons and related military technologies. Such complexities include, for example, the definitions and regulatory procedures to identify and classify materials designed, developed, configured, adapted, or modified for a military application (Larkin, 2013). In addition, there are complications related to the identification of dual-purpose products, i.e. those designed primarily for commercial use, but could have military applications, and any communication of controlled information or technology to a foreign national within the U.S.

As an industry expert explained, "So now we have an issue where the things that are going into military programs have the same specifications as product that goes into golf clubs, tennis rackets, and sporting goods, automotive, and windmills. So that's a problem for the regulators, is how do they make sure they keep this item from going to things they don't want it to go to while letting the civil end use commercial trades flourish". Mandatory export law licenses take into consideration whether the product in question is listed as an export control, whether one of the parties in the transaction is on the exporting country's blacklist, and if the product's end-use is controlled. Compliance of such regulations is thus no easy task, and yet failure of doing so can lead to up to $1 million in penalties and result in imprisonment (Larkin, 2013).

We found that carbon fibre exporters have expressed concerns over the impact of export controls on green technology items. These include extended processing times and difficulty in obtaining licenses for carbon fibre, wind turbines and lighter weight material and equipment, commercial composite aircraft structures and energy efficient engine components (Gross, 2011). A survey conducted by the U.S. department of commerce with carbon fiber producers, distributors, composite product manufacturers, and other carbon fiber-related stakeholders, found that required certifications add restrictions and barriers to market entry, especially to smaller businesses (U.S. Department of Commerce, 2015). This survey also found that U.S. and European environmental and remediation regulations were a significant concern primarily for very large businesses. Such regulations included the U.S. Environmental Protection Agency (EPA), U.S. Department of Transportation (DOT), and the European Chemicals Agency (ECHA). In addition, respondents suggested that there were major supply chain challenges because environmental restrictions on their suppliers make it difficult to find some materials. Overall, the document concludes that qualifications and certifications issues were the second most important organizational challenge, preceded by concerns over the governmental product demand, their main costumer.

7. Discussion and recommendations

We began this study by exploring an apparent paradox, where improved price performance characteristics recognized by Moore's Law versus the actual costs of regulatory approval and other downstream commercialization costs (as illustrated by the Eroom effect) may actually hinder sustainable technology development. Consistent with the economic theories of regulations and capture (Stigler, 1975; Carpenter, 2004), publically funded institutions such as university and government labs attempting to develop more sustainable technologies may thus be at a disadvantage over large incumbent organizations. This is quite disconcerting, given that publically funded research could otherwise be an important driver of more sustainable technologies (Manjunatha et al., 2015). Paradoxically – and similarly disconcerting – it appears as if policy efforts to stimulate more sustainable technologies are being hampered by regulatory policies designed to protect public safety, but as a side effect provide advantages to large established organizations that dominate incumbent, less sustainable technologies.

The reasons for this paradoxical situation is as follows. First, while many scholars recognize that sustainable development pressures are a stimulus and incentive for creative destruction, most studies suggest that environmental innovations provide lower returns when compared to non-environmental innovations (Marin and Lotti, 2016; França et al., 2017). Consistent with the traditional economic theories of regulation of for example Pigou (1932) and Stigler (1975), Porter and Van der Linde (1995) have argued that strict regulations could stimulate innovation, improving environmental and economic performance. Ambec et al. (2013) however found there was not much evidence that the Porter Hypothesis enhanced business performance. Thus, while the literature suggests that innovation is a much more appealing and politically feasible mechanism when compared to alternatives, the commercial viability for more sustainable innovations is still elusive.

For transgenic cotton, there appears to be some commercially viable attributes if large scale farming is the primary market, while sustainability relevant markets, in the form of small-scale, impoverished farmers, albeit less financially lucrative, could provide enormous social value. However, while the societal benefits could be considerable, the onerous and expensive downstream costs may not warrant further development. A similar case can be made for lignin-based vanillin, where the relatively small market populated with numerous options ranging from low cost to premium products, would be discouraging for any new entrant if only economic criteria were used for decision-making. For lignin-based carbon fibers, the technological hurdles, and thus R&D investments remain substantial, while competing alternatives are currently more advanced and more suitable for the lucrative aerospace and defense sectors. Thus, without their improved sustainability characteristics, it is unlikely that any of these lignin-based technologies would be taken seriously by investment communities.

A second theme identified from our literature review is the importance of industrial and national contexts. Responding to calls to address these differences and related specificities (Przychodzen and Przychodzen, 2015; Cheng et al., 2014), we analyze cases from two different countries, Brazil and Canada, with varying degrees of economic development, and in various industrial contexts (agriculture, food additives and carbon fibers for automotive, aerospace and defense applications). In contrast to much of the literature, we did not find significant national differences due to each case's respective regulatory regime; the Eroom effect applied equally to both countries. We speculate this may be due to an increased influence of international regulatory standards or harmonization. For the Canadian cases, there was a recognition that focusing solely on the Canadian market would be too restrictive, given the country's integration with trading partners. For the Brazilian case, it appears as if NGO opposition to transgenics has become globally seamless. Silvestre (2015a, 2015b) argues that high levels of complexities and uncertainties represent additional barriers to sustainable development; unfortunately for Brazil, when it comes to opposition to transgenics, there is not much difference to developed economies.

More pronounced was the industrial context. For example, transgenics has been highly controversial, and as a result there have been increasingly stringent regulations. This is consistent with the pharmaceutical industry but in sharp contrast to for example electronics, where Moore's Law is more apparent (Fichman et al., 2014). In addition to safety and efficacy challenges of the CFIA and/or the U.S. Food and Drug Administration's regulatory approval process, vanillin needs to meet the more nuanced and perhaps ambiguous definition of 'natural' in order to be commercially viable. Similarly the carbon fiber case needs to grapple with complex U.S. export control policies, even if their primary applications are not in defense-related fields.

An approach used in carbon fibers is the use of consortia to develop technology. The innovation literature emphasized that such alliances can bring together requisite complementary assets necessary for successful innovation (Teece, 1986). This may be the case for less controversial technologies like carbon fibers, but we caution publically funded labs to get too close to commercial enterprises that have been the target of public controversy, as is the case in transgenics. While Carpenter (2004) notes that familiarity with regulators may trump a bad reputation, it may not be enough to overcome public opposition. For example, partnering with Monsanto, the main target of NGO opposition (Bunge, 2016), did little to advance Golden Rice, even though they possessed all of the necessary complementary assets to bring it to market (Hall et al., 2014a). Industry context thus matters when it comes to consortia for sustainable innovation.

7.1. Limitations and future research

This research is limited by focusing on two countries and two technologies applicable to a relatively narrow industrial context. Further research could expand the national and technological scope, to determine how pervasive the EROOM effect has become. It would also be useful to explore in greater depth longitudinal issues. In our study we discussed technologies at an early stage of their development, as well as a more mature R&D program. More detailed investigations conducted over a greater length of time would provide useful insights on how technologies evolve in response to regulatory pressures, and how this is shaped by civil society.

We also acknowledge that, although the main value proposition of the selected cases were based on potential sustainable attributes (e.g. renewable, lower potential CO_2 emissions, opportunities for poor communities, etc.), further technical studies such as life cycle assessments are needed to support such claims. Even if such studies provide evidence that the new technologies offer improved environmental and societal characteristics, additional studies would be needed to explore if rebound effects (Vivanco et al., 2015) and other unanticipated outcomes could negate these potential benefits. In the vanillin and carbon fiber cases, we speculate that the adoption of the lignin-based technologies would not stimulate a material increase in the size of the market, and thus rebound affects should be negligible. The cotton case is perhaps more complex. For example, if successful, the technology might allow the industry to return to pre-boll weevil production levels, thus offering positive environmental and social rebound effects. However, it might for example also set a precedent for more transgenic crops that offer only marginal environmental benefits, but expand productivity into protected areas such as the Amazon rain forest, encourage intensive mono-crop agriculture or undermine organic farming.

A related area worthy of further research concerns the ethical dimensions of new technology development, and how this influences the Eroom effect. For example, there appears to be tension between those that deem natural labelling as meeting objective criteria, versus those that see it as analogous to organic, traditional farming practices, i.e. exclusive to vanilla bean production or organic cotton using traditional (non-transgenic) breeding techniques. At issue here is whether consumers are able to make an informed choice. A related proposition worthy of further research is whether a potentially more sustainable innovation's legitimacy (Hall et al., 2014a) may be undermined if utilized in dubious applications. For example, assuming carbon fibres have superior environmental performance, would this technology's environmental benefits be negated if used in military applications that undermine human rights? This does not appear to be the case for other materials such as aluminum and titanium, but perhaps more prominent with for example Agent Orange, a herbicide used by the U.S. military in Vietnam.

Further research should explore how NGOs and public pressure have exacerbated the Eroom effect, and specifically whether it has paradoxically hindered the development of more sustainable technologies. In their noble efforts to rectify unrestrained economic development at the expense of the environment and social well-being, did NGOs inadvertently throw the baby out with the bath water? Perhaps NGOs could start to focus their attentions less on specific technologies and instead support institutions attempting to develop more sustainable technologies, castigate those that hinder such efforts, or focus their attention on applications rather than the technology *per se*.

Policy makers sponsoring sustainable innovation through government research labs and universities may have to come to terms with the need for greater funding for downstream costs, however unpalatable that may be to their fiscal agendas. This should not simply be a re-allocation of resources from scientific efforts to commercialization and regulatory approval activities (the costs associated with scientific endeavor remain formidable, and continuously grow with scientists' aspirations), but additional funds to ensure that the last steps of commercialization allow promising technologies to achieve their societal contributions. This is perhaps particularly pertinent for university research developing sustainable technologies for industries less attuned to academic research, what Hall et al. (2014b) call passive industries.

Another alternative is whether priorities can be allocated to expediting the approval of more sustainable technologies, particularly if they are developed by government labs. According to Scannell et al. (2012), one period when approvals deviated from the Eroom effect was when AIDS treatments were expedited through regulations, in response to pressure from organized AIDS sufferers (Carpenter, 2004). Note that more expedient regulatory approvals remain contentious and are associated with increased serious adverse drug affects (Olson, 2008). Furthermore, whether sustainable innovations can evoke the urgency of AIDS or other devastating pandemics such as Ebola[2] warrants further research.

8. Conclusions

We responded to calls for providing a greater understanding of the challenges associated with innovation that improves ecological and societal sustainability, by focusing on the downstream costs that are often underestimated by those developing the technology. The challenges of technological innovations are increasingly less about overcoming scientific and engineering hurdles, and more about the often complex regulatory approval (transgenic technology), labelling (natural vanillin) and trade restriction policies (lignin-based carbon fibers) processes. In the case of transgenic cotton, we found that although technologically feasible, gaining regulatory approval may be prohibitive. While there is a need and potential for substantial social and environment improvement, there remain concerns about commercial viability within these markets, and whether the societal benefits will be undermined by regulatory barriers, which in turn have been shaped by anti-GMO activism. For food additives, a key attribute is whether the technology can be framed as a natural ingredient, otherwise it cannot compete against low cost synthetic alternatives. Carbon fiber applications are highly dependent on the industry context, where for example regulatory approval and trade restrictions in defense and aerospace applications are substantially high.

The apparent paradox of Moore's Law versus the Eroom effect of regulations and downstream commercialization costs is emerging as a major, but typically underestimated, challenge for sustainable innovation. Publically funded institutions such as university and government labs – key drivers of more sustainable technology – need to be aware of these hurdles and allocate resources to overcome them. Policy makers also need to recognize that their efforts to stimulate more sustainable technologies may be hampered by regulatory policies that, albeit with good intentions, may provide advantages to established organizations focused on less sustainable technologies. Finally, NGOs might also reflect on how their efforts to improve sustainable business practices may have resulted in barriers for more sustainable technologies.

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[2] Thanks to Perri 6 for this useful suggestion.

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