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Environmental finance: A research agenda for interdisciplinary finance research

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ABSTRACT

Environmental Finance is an emerging and rapidly growing interdisciplinary field of research, concerned with the financial implications of environmental change for industries and firms, and the need to transition to a sustainable economy. The field brings together research in finance and the natural sciences to develop financial and market solutions to some of humanity's most pressing concerns; namely, climate change and shifts in other Earth system processes. Firms need to adjust to these environmental changes, which offer many opportunities for wealth and growth. There are various historical examples of technological breakthroughs over the history of modern markets that have driven growth and wealth; such as, railways, electricity, automobiles, radio, microelectronics, personal computers, biotechnology, and the internet. The 2015 Paris Climate Agreement has given the green light to clean technology firms worldwide to start commercializing their patents. This will create the next technological breakthrough – a clean tech revolution that will drive growth and wealth in the same way as earlier breakthroughs. This article summarizes the state of this newly formed interdisciplinary field and sets out avenues for future research.

1. Introduction

Recent scientific findings have generated significant concern about the level of global environmental change driven by direct human-induced impacts on ecological systems. In 2009, researchers introduced a planetary boundaries framework (Rockström et al., 2009) which defines the limits (or boundaries) of human modification of critical Earth-system processes. These boundaries cannot be transgressed if we are to retain a "safe operating space" for global societal development. Fig. 1 illustrates these Earth-system processes: climate change, biosphere integrity, land-system change, freshwater use, biochemical flows (release of phosphorous and nitrogen into the atmosphere), ocean acidification, atmospheric aerosol loading, stratospheric ozone depletion, and the introduction of novel entities into the environment (new substances, new forms of existing substances, and modified life forms) (Steffen et al., 2015). As more and more of these system boundaries are transgressed, society faces greater risks of adverse environmental change, possibly on a global scale. The consequences of rapidly increasing human pressure on the planet are already visible and include observed changes in regional weather extremes and ecosystem degradation due to chemical and fertilizer pollution. Other changes have started to manifest globally, such as more intense, frequent, and longer-lasting heat waves (Perkins et al., 2012). The economic impacts are expected to be significant (Sterner, 2015).

The potential shift from desirable to undesirable states for human development (possibly even at a global scale) points to the urgent case for societal action, especially in less developed countries where adaptive capacity is low. The risks have been recognized as real—an international architecture has been established to provide climate adaptation and mitigation funding to developing countries and encourage technological knowledge transfer (e.g., Cui and Gui, 2015; Eyckmans et al., 2016; Locatelli et al., 2016; Markandya et al., 2015). The key agents behind the accelerated pace of change are not just individual humans and their consumption patterns, but organized human industrial activity in form of the human enterprise, which significantly expanded after the Second World War. Since 1950, the world's population doubled to reach over 6 billion people by the end of the 20th century. Over the same period, global economic activity increased by more than fifteen-fold (Steffen et al., 2007). Industrialization has brought great benefit to many, especially in developed economies. This phase is sometimes known as "The Great Acceleration" (Steffen et al., 2007) and is characterized by rapid increases in total real GDP, foreign direct investment, resource consumption, and fossil fuel use. At the same time, humans have changed the world's ecosystems more rapidly and extensively than ever before.

The human enterprise now dominates much of modern life; however, a large proportion of the world's population continues to live in absolute poverty and environmental degradation has reached planetary

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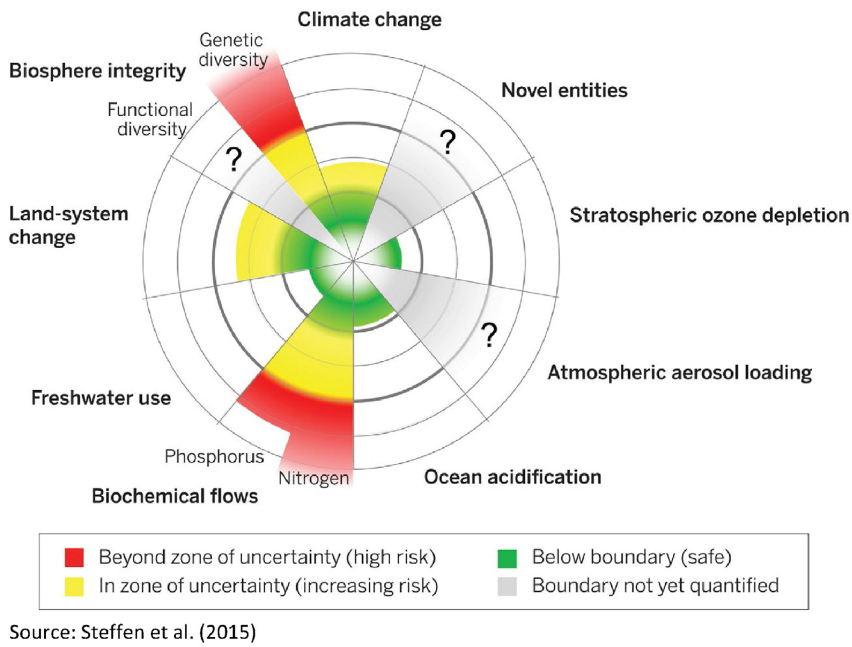

Fig. 1. Planetary boundaries. Source: Steffen et al. (2015).

scales. The Great Acceleration has reached a critical point, and serious planetary-scale threats need to be dealt with proactively. And the case for action is not just a moral imperative to preserve the integrity of Earth's systems for future generations. More immediately, firms and industries face significant challenges (Whiteman et al., 2013). The severity of global environmental change suggests drastic responses, both in terms of mitigation (i.e., reducing impacts on the environment) and adaptation (i.e., adjusting to the impacts of environmental change). Environmental Finance is an emerging and rapidly growing interdisciplinary field of research concerned with the financial implications of environmental change for industries and firms, and the need to transition to a sustainable economy where humanity lives within the boundaries of our Earth system (Linnenluecke et al., 2016).

This paper sets out the research agenda to accompany this transition. Firms need to adjust to these environmental changes, which do not present significant threats but also many opportunities. Hong et al. (2008) identify many historical examples of technological breakthroughs that have driven growth and wealth; such as railways, electricity, automobiles, radio, microelectronics, personal computers, biotechnology, and the internet. The 2015 Paris Climate Agreement has given the green light to firms worldwide to start commercializing their clean technology patents. Indeed, there are already over 500,000 clean technology patents worldwide, most held by firms in Europe, China, and the US. Clean technologies cover a range of solutions from renewable generation and smart grid technologies through green chemistry and water treatment. This will create the next technological breakthrough – a clean tech revolution that will drive growth and wealth in the same way earlier breakthroughs.

2. Literature review

Throughout the history of human enterprise, industrial activity has largely been conducted with little thought to potential impacts on the natural environment. Since the Industrial Revolution, a growing manufacturing base has consumed increasing environmental resource inputs; however, society has only recently begun to consider the full impact of (aggregate) industry action on global environmental change. It is only in more recent times that we have admitted the possibility that a changed environment may have consequences for firms and industries operating in vulnerable sectors (Winn and Kirchgeorg, 2005). This is despite the fact that nineteenth century economists had already recognized that unsustainable levels of resource consumption could lead to adverse environmental changes and associated negative outcomes for society (Malthus, 1878; Marsh, 1864; Mill, 1848). Indigenous knowledge about the negative impacts of human activity on the environment dates back even further and recognizes the importance of self-regulatory mechanisms once a society is faced with resource limitations (Gadgil et al., 1993).

2.1. The impact of economic activity on the environment

Systematic efforts to identify the impacts of economic activity on the environment began in the 1960s when global ecological problems first became highly visible. Carson (1962) raised public awareness about the severity of environmental degradation and is often cited as a catalyst for the environmental movement of the 1960s and 1970s. Carson's work detailed how agrochemicals (in particular, pesticides such as DDT) contaminated the food chain and compromised animal and human health. Simultaneously, scientific research began to draw attention to other significant social and environmental problems, such as rapid population growth (Ehrlich, 1968), species extinction (Ehrlich and Ehrlich, 1981; Holdren and Ehrlich, 1974), pollution, and acid rain (Likens and Bormann, 1974). Scholars also began asking how those negatively affected by these problems should be compensated (Coase, 1960; Dales, 1968). The extent of these problems not only triggered the environmental movement, but was recognized at an intergovernmental level at the 1972 United Nations Conference on the Human Environment. The aim of the conference was to quantify global human impact on the environment and to define principles for guiding environmental preservation efforts. One of the most important outcomes of the conference was the establishment of the United Nations Environmental Programme (UNEP) in 1973.

Corporations were generally regarded as the actors with the reach, resource access, technology, and motivation to help solve environmental (and social) problems (Hart, 1997; Hawken, 1993); albeit these issues were recognized to be beyond the scope of any individual firm, particularly the challenges associated with rapid economic development and population growth in developing countries. Building on Carson's work, economists began to debate whether economic systems sufficiently accounted for environmental externalities, giving rise to the field of ecological economics (Costanza and Daly, 1987; Pearce, 1987). Some economists went so far as to propose a shift towards a 'steady state economy', with stagnant or even decelerating economic activity (Daly, 1973, 1974; Meadows et al., 1972; Victor, 2008). In the 1970s and 1980s, governments in developed economies introduced environmental regulations that required firms to create and finance internal environmental compliance functions, leading to some of the first attempts to implement social and environmental accounting systems. However, many firms lobbied against these regulations, arguing that the new standards were an unwarranted impost on doing business (Walley and Whitehead, 1994).

2.2. The emergence of eco-efficiencies

From the mid-1980s, firms began to change their behavior as they saw opportunities to profit from easy (but often very significant) cost savings from pollution control and waste reduction processes (Walley and Whitehead, 1994). These responses were referred to as "beyond compliance" (e.g., Russo and Fouts, 1997) and "market-driven environmentalism" (Post and Altman, 1994: 65), because corporate decisions were driven by market incentives (in particular cost savings and enhanced efficiencies), rather than regulatory compliance. The concept of generating environmental benefit via more efficient resource use and consumption became known as 'eco-efficiency'. This term was coined by the World Business Council for Sustainable Development in its 1992 publication "Changing Course". The pursuit of eco-efficiencies gave rise to a significant debate about the potential for 'win–win' opportunities; that is, whether improving corporate environmental performance could also improve corporate financial performance. Some scholars questioned the win–win paradigm with evidence that eco-efficiency improvements did not automatically translate into improved environmental performance, due to overall growth in consumption (Schot et al., 1997; Starik, 1995). The implementation of eco-efficiencies was accompanied by the introduction of environmental management systems (e.g., ISO 14001), more sophisticated types of environmental performance analysis and reporting (e.g., life-cycle analysis), and more extensive stakeholder engagement (Fischer and Schot, 1993; Starik and Marcus, 2000).

2.3. The era of global risk

The late 1980s and early 1990s marked the beginnings of an era of global risk. The environmental movement of the 1960s and 1970s was largely motivated by public, media and stakeholder attention to environmental pollution that was highly visible, yet often local or regional and reversible. The discovery of the ozone hole and the realization that climate change was posing a long-term threat were based on scientific findings (rather than on publicly visible environmental problems), and pointed to significant degradation on a planetary scale (Bodansky, 2001). In 1987, the World Commission on Environment and Development (WCED) promoted the idea of "sustainable development", defined as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). In 1988, the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO) established the Intergovernmental Panel on Climate Change (IPCC) in an attempt to bring together international experts to assess the state of knowledge on climate change. The first IPCC report released in 1990 found a significant body of evidence to support the argument that human activities were inadvertently changing the climate of the globe. These developments culminated in the 1992 United Nations Conference on Environment and Development (UNCED) and the United Framework Convention on Climate Change (UNFCCC). Both meetings significantly impacted the international policy agenda and led to many countries adopting national climate policies.

The UNFCCC Kyoto Protocol was adopted by most industrialized nations in 1997 and came into force on 16 February 2005. The Protocol set a binding goal of limiting greenhouse gas emissions to at least 5% from 1990 levels over the period 2008–2012. As a result, some jurisdictions (e.g. the European Union) have already introduced regulations to limit carbon–intensive processes. At the same time, research attention shifted to developing new business models that would limit resource and consumption, and ultimately even positively contribute to the planet's ecosystems. Gladwin et al. (1995: 891) argued that firms should adopt a sustainability-focused, or 'sustaincentric', management paradigm and operate within biophysical (natural) limits. Hart (1995) challenged the traditional resource-based (or consumption-oriented) view of the firm and proposed a natural-resource based view which considers the constraints imposed by the biophysical (natural) environment (see also Hart, 1997). In 1999, Hawken et al. published "Natural Capitalism", which attempted to link "nature" with the core economic and finance concept of "capital". Their work proposed that business practices should drastically increase natural resource productivity by adopting biologically inspired production models (closed-loop manufacturing), adopting a service mentality, and reinvesting in natural capital. The idea of natural capital led to significant debates regarding whether or not market mechanisms are best suited to solve environmental problems (see Millward-Hopkins, 2016). The interdisciplinary field of ecological economics also began to pay attention to the value of natural capital, with efforts to measure and value ecosystems globally. However, attempts to integrate natural capital within existing financial frameworks have not yet been operationalized.

3. Towards a research agenda in environmental finance

There is increasing evidence that climate change and other planetary boundary violations are significantly altering the operating environment for many firms. To tackle the challenges of global environmental change, several scholars have called for new transdisciplinary foundations to develop powerful insights that extend beyond narrow disciplinary boundaries (see Winn and Pogutz, 2013). Environmental Finance is one attempt to combine insights across the economics, finance, organizational strategy, and science disciplines to help tackle some of our most pressing environmental and social risks. For instance, climate change puts corporate assets at greater risk, due to more frequent and severe extreme weather events. Economic activity will also be affected by the flow-on effects of climate change, such as regulatory resource constraints (e.g., limits to fossil fuel extraction and other types of carbon constraints) (Linnenluecke et al., 2015a). Some investor reports (e.g., Carbon Tracker Initiative) already note that fossil fuel companies may face restrictions on extracting fossil fuel reserves; thus, potentially limiting future exploration (Linnenluecke et al., 2015a). At the same time, there are opportunities in the shift towards more environmentally-friendly technologies and cleaner energy systems (Linnenluecke et al., 2015b).

3.1. Regulatory impacts

An important stream of Environmental Finance research considers which measures are most effective for stabilizing and reducing environmental impacts (Li and Jia, 2016), and how to encourage investment in new technologies and solutions, such as clean energy infrastructure (Bertram et al., 2015; Bohringer et al., 2015; Jones, 2015). Legislative and international funding efforts proved successful in the case of the stratospheric ozone depletion boundary (Dixon, 2011). The signing of the Montreal Protocol on Substances that Deplete the Ozone Layer (the Montreal Protocol) was an international effort to address the ozone hole, which has led to the implementation of measures for phasing-out ozone-depleting substances. As a result, the minimum ozone concentration has now been steady for about 15 years, and it is expected that the ozone layer might be eventually restored (Steffen et al., 2015). However, other Earth-system processes have been in steady decline, and four planetary boundaries have now been breached. Although the Kyoto Protocol has its critics, it was an important first step towards a global regime to tackle climate change, because it led to the creation of national carbon markets and introduction of other economic measures to reduce carbon. The Paris Agreement was adopted in 2015 and (once ratified by the signatories) will govern emission reductions from 2020 onwards, via country commitments in ambitious nationally determined contributions.

The emerging policy landscape for action on planetary boundary violations provides a rich context for future research. For instance, there are lessons to be learned from the Montreal and Kyoto Protocols about designing and implementing international treaties, and about tackling breaches in other planetary boundaries. Furthermore, the evolving international policy landscape for climate change mitigation and the development of carbon finance markets (Bredin et al., 2014) deserve future research attention. Since the first Emissions Trading Scheme (ETS) was introduced in the European Union (EU) in 2005, many other schemes have been implemented across North America and Asia (e.g., Paterson, 2012; Song et al., 2015). A total of 47 countries (including the 28 member states of the EU) have a carbon pricing system in place, either through a carbon tax or a cap-and-trade system (Nachmany, 2015). The US state of California began enforcing a cap and trade program in January of 2013. The Canadian province of Quebec has joined this initiative and Ontario has launched plans to do so in 2017. Several other jurisdictions are considering implementing an ETS (ICAP, 2015). The existing schemes have revealed many practical considerations; for instance, how to recognize carbon allowances in financial accounting frameworks (Lovell, 2014; Lovell et al., 2013; Warwick and Ng, 2012).

China is the world's biggest greenhouse gas (GHG) emitter; it has implemented several pilot ETS schemes and recently announced the implementation of a national ETS. This could be a turning point in action on climate change (Huang and Bailis, 2015) and is a natural experiment for ongoing monitoring. The widespread implementation of ETS and carbon taxes, as well as voluntary company action, raise questions about the implications for economic activity and firm performance on international, regional, national, and local levels (Gallego-Alvarez et al., 2015; Gallego-Alvarez and Segura, 2015). The implementation of the Chinese ETS is a significant commitment to mitigation by a major emitter; nevertheless, some researchers (e.g., Phelan et al., 2010) are concerned that market approaches to limiting carbon emissions may not set sufficiently stringent permissible limits on greenhouse gases thereby failing to fully consider planetary boundary constraints. The relationship between market approaches to mitigating climate change (or other types of environmental impacts) and the planetary boundary framework is yet to be explored.

3.2. Asset impairment

A second major stream of Environmental Finance research considers how breaches of planetary boundary conditions impact corporate assets. Data from the IPCC show that anthropogenic GHG emissions have significantly increased since the Industrial Revolution, and that CO_2 emissions from the combustion of fossil fuels and other industrial processes contributed about 78% of the total increase in global GHG emissions from 1970 to 2010 (IPCC, 2014). Scientists debate the magnitude of climate change in the absence of mitigation (Tokarska et al., 2016), and the level of fossil fuel use and associated GHG emissions that can be emitted without risking 'dangerous anthropogenic interference with the climate system' (e.g., Allen et al., 2009; McGlade and Ekins, 2015; Meinshausen et al., 2009). The internationally-agreed upper target for limiting global mean temperature increase is 2 °C relative to pre-industrial levels (with efforts to limit warming to 1.5 °C). The target is commonly considered to be a 'safe' level of temperature rise based on the assumption that adaptation to climate change can occur at acceptable costs. However, this assumption has been criticized for committing the world to significant climate change (Hansen, 2005; Randalls, 2010). The planetary boundaries framework suggests that the boundary values for climate change are "an atmospheric CO_2 concentration of 350 parts per million (ppm) and an increase in top-of-atmosphere radiative forcing of $+1.0$ W m^{-2} relative to preindustrial levels" (Steffen et al., 2015), which are estimated to result in much lower levels of warming (Hansen and Sato, 2012).

Concerns about the environmental impact of burning fossil fuel reserves have sparked a worldwide divestment movement (Linnenluecke et al., 2015b; Ritchie and Dowlatabadi, 2014); however, the scientific debate about possible limits on fossil fuel consumption have created apprehension that fossil fuel infrastructures might become 'stranded' assets. Estimates suggest that fossil fuel companies have proven reserves of nearly 3000 gigatons of CO_2 (defined as those fossil fuel resources that can be recovered with current technologies at current prices), and burning these reserves would greatly exceed the 2 °C target (Allen et al., 2009; Meinshausen et al., 2009). If humanity is to remain within the target of 2 °C with a 50% probability, then less than half of these reserves can be burned in the future (Meinshausen et al., 2009). Griffin et al. (2015) examined how the stock market reacted to this prediction and found a significant negative reaction of 2.48% or U$27 billion in the value of energy firms. Nevertheless, they point out that this negative effect – while significant – is well short of what one would have expected given the dire warnings by Meinshausen et al. (2009).

The effect of limits on fossil fuel consumption will create stranded asset values for energy firms, but the market is likely to be very perceptive in incorporating this risk into price. If we denote p_t as the probability of collective action on climate change (i.e., keeping within a target of 2 °C) then the observed market price P_t is given by:

$$P_t = p_t P_t^S + (1-p_t) P_t^{NS.}$$

where P_t^S is the stranded asset value and P_t^{NS} is the non-stranded asset value. Thus, we see that the observed market price is a probability-weighted average of the stranded asset price and the non-stranded value. Simply examining price changes resulting from announcements and publications such Meinshausen et al. (2009) will overlook the interaction of all three parameters – the effect of the publications on the probability of effective action on climate change, p_t, the effect on stranded asset value, P_t^S, and the effect on non-stranded asset value, P_t^{NS}. Since the above observed transaction price is a function of these three parameters, a technique needs to be developed to identify the parameters and uncover their values. We suggest that a fruitful area for future research will be examining parallel fields, such as the takeover literature (Barraclough et al., 2013), for the parameters that are uncovered on the announcement of a takeover.

Researchers have also started to estimate the potential environmental impacts of investment decisions (Ritchie and Dowlatabadi, 2014), as well as the impact of climate change on financial assets, by defining a measure for Value at Risk (VaR). The VaR measure quantifies "the size of loss on a portfolio of assets over a given time horizon, at given probability" (Dietz et al., 2016). This measure has so far been applied to estimate the VaR of global financial assets (under a business-as-usual emissions pathway the value is estimated to amount to US$2.5 trillion) (Dietz et al., 2016). However, the VaR is also applicable to other types of asset portfolios and asset management; for example, in the banking sector or assets under management by investment funds. Breaches of the planetary boundary conditions are likely to threaten business assets, profits, and human capital, so an important area for future research will be calculating the VaR for the eight boundary conditions.

3.3. Adaptation to change

A third major stream of Environmental Finance research concerns the need to adapt to environmental change. Adaptation will be especially important in developing countries which have limited adaptive capacities, technical expertise, and funding (Biggs et al., 2013; Jost et al., 2016). The developed world will also have to adapt, particularly in vulnerable sectors and locations (Hagerman, 2016; Hodgkinson et al., 2014; Lyle et al., 2015). For firms, the adaptation imperative arises from the need to manage risks in order to minimize the physical impacts of environmental change (climate change impacts, water scarcity, increased risk of droughts and floods). Adaption is also motivated by the need to adjust to new technological developments, such as clean energy (see below). Future research can estimate the costs and benefits of adaptation (including replacement values) (Kumar and Taylor, 2015; Mekonnen, 2014) and evaluate how to direct adaptation investments, given an uncertain and volatile future. This includes assessing which adaptation options should be undertaken for what type(s) of climate impacts (Nelson et al., 2013), considering whether adaptation should be undertaken and financed by private or public investments (Antle and Capalbo, 2010; Pauw et al., 2016), and evaluating the possible cost–benefit trade-offs associated with adaptation (e.g., Borgomeo et al., 2016; Scott and Weston, 2011).

Another important area of future research is the international architecture for adaptation funding. Several funds have been established to assist developing and least-developed countries to adapt to climate change, including the Special Climate Change Fund, the Least Developed Countries Fund, the Green Climate Fund, and the Kyoto Protocol Adaptation Fund. These funds are essentially mean to support action on climate change. However, the international climate finance architecture has become difficult to trace, and researchers have questioned the equity and efficiency of fund allocation. Other scholars have pointed out that adaptation funding must be integrated with socio economic development (Fankhauser and Schmidt-Traub, 2011; Hoffmaister and Roman, 2012). Research can greatly contribute to questions around the optimal governance of funds, fund allocation, and the integration of adaptation and mitigation. Another important avenue for future research is the role of industry in adaptation (Keskitalo et al., 2014; Surminski et al., 2016), especially the role of the insurance industry and governments in coordinating adaption efforts.

3.4. Managing increased volatility

Environmental changes do not just manifest as changes in the mean (e.g., mean temperature) but also as changes in volatility (e.g., intensity, frequency, and duration of heat waves globally). A fourth major stream of Environmental Finance research concerns the impact of increasing volatility on stock markets, as well as systemic risks for vulnerable sectors. Data from the US National Oceanic and Atmosphere Administration (NOAA) show that weather extremes account for significant losses - 2015, there were 10 such events with losses exceeding $1 billion each across the United States alone.[1] As environmental volatility grows, risk transfer solutions have become key tools for measuring vulnerability, including geographical diversification (Tang and Jang, 2011), as well as financial hedging techniques, such as insurance solutions (Collier and Skees, 2012), weather derivatives (Bank and Wiesner, 2011; Bertrand et al., 2015; Isakson, 2015; Pollard et al., 2008) and catastrophe bonds (Johnson, 2014, 2015). In the stock market, investors are able to hedge volatility risk by using derivative products based on the Volatility Index (VIX) index. An important issue for further research is whether a volatility index for climate and environmental change would serve a similar purpose or whether it would be better to develop more localized volatility measures that are tailor-made for the specific environmental conditions facing a particular firm or industry (Ray et al., 2015).

3.5. Valuing opportunities

The 2015 Paris Climate Agreement provided a clear signal to the owners of clean tech patents that it was time to shift into commercialization mode. However, it is difficult to use traditional valuation methods (e.g., cost/benefit and discounted cash flow techniques) to value these patents and the companies that own them. Clean tech projects require significant research and development, and usually an approval stage as well. At the commercialization stage, breakthrough success is possible, but so is total market failure. Real options analysis seems to be an appropriate way to value these opportunities and companies, because the process of discovery, approval, and commercialization involves a series of real options. Brennan and Schwartz (1985); McDonald and Siegel (1985); McDonald and Siegel (1986), and Titman (1982) have published seminal papers on real options analysis, which could be extended to the clean-tech opportunities described above.

There are several approaches to valuing real options. The first is to use analytical option-based models based on Black and Scholes (1973) and Merton (1973). These analytical formulas are able to capture the flexibility inherent in real options; however, for more strategic options, the formulas are too complex and specific to the valuation at hand to be easily generalized. Simulation analysis (e.g., Schwartz and Moon, 2000) is a more generally applicable valuation program in which the flexibilities in the valuation can to be adjusted. A third approach to valuing real options is decision trees (Kellogg and Charnes, 2000). The advantage of decision trees is that they mirror the strategic options as and when they occur and incorporate the decisions that need to be made in terms of, for example, expansion, delay, or abandonment. Future research can investigate which of these approaches is suited to valuing clean-tech opportunities and what adjustments need to be made to the valuation methodologies.

Another important area of research is to consider how the clean-tech revolution will unfold over time. Gunderson and Holling (2002) outline four phases of transformation which can be applied to technological breakthroughs such as the automobile (see also Hong et al., 2008). The four phases are (i) rapid growth, (ii) a period of stability, during which time the industry becomes less resilient, (iii) creative destruction, otherwise known as a post-bubble market crash, and (iv) a period of renewal. Ofek and Richardson (2000) offer another explanation for what happens during technological breakthroughs. They argue that the market is dominated by optimistic investors who over-bid the price of firms involved in the technological breakthrough. The rational investors are unable to correct this as there are insufficient shares to short in these relatively new start-up companies. This enables the market to rise to unjustified heights; and the resulting bubble burst is an inevitable correction. Hong et al. (2008) offer a third theory; they characterize advisors as either 'tech-savvies' or 'old-fogies'. Tech-savvy advisors overhype the market for technological breakthrough stocks and old-fogies tend not to get involved in new markets they do not understand – or, if they do, they downgrade the valuation to such an extent that they are not believed. Again, this causes the market to overheat, with a resulting market crash correction. The imminent clean-tech revolution offers ample opportunities to test and expand on these various theories, and to develop new theories.

4. Conclusion

This paper reviews the emerging research area of Environmental Finance. It shows how this field links to the planetary boundaries framework (Rockström et al., 2009; Steffen et al., 2015) and summarizes the significant body of science underlying this framework. The paper also outlines the opportunities of the clean-tech revolution, which will rival the technological breakthroughs of the past (Hong et al., 2008) and drive wealth and growth over the next generation. We have

[1] Updated data are available via: http://www.ncdc.noaa.gov/billions/events.

outlined promising areas for future research in the areas of regulatory impacts, asset impairment, adaptation, climate volatility, and the valuation of clean-tech opportunities.

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