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Green R&D for eco-innovation and its impact on carbon emissions and firm performance

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ABSTRACT

Over the past four decades, the results of the debates about the relationship between corporate environmental performance and corporate financial performance have remained inconclusive, due to the lack of theoretical underpinning and availability of data. This paper examines the impact of green research and development investment for eco-innovation on environmental and financial performance. The research is based on the resource-based view and the natural resource-based view, which explicitly recognize the importance of resources and capabilities. Using a sample of Japanese manufacturing firms during the period of 2001–2010, the study focuses on green research and development investment as a key proxy of eco-innovation and carbon emissions in environmental performance. Our results show the presence of a negative relationship between green research and development and carbon emissions, while green research and development is positively related to financial performance at the firm level. Our findings explicitly support that, in order for firms to adopt a proactive environmental strategy to manage their environmental and financial performance to the best advantage, they urgently need to organise unique resources and capabilities. The findings of this study provide valuable insights and basis of scientific debate on how firms to engage unique organizational resources and capabilities for superior corporate environmental and financial performance.

1. Introduction

Global warming and its impacts on society in general leave little doubt that businesses play a major role in delivering environmental performance outcomes through production, operations, and efforts to achieve innovations of more sustainable products and practices (Hart, 1995; Porter and van der Linde, 1995; Klassen and McLaughlin, 1996; Lee, 2009; Busch and Hoffmann, 2011; Lee and Kim, 2011). Despite the importance of global warming and firm's innovation efforts, empirical studies using firm level data have been scant. This is largely due to the difficulty of obtaining data. Our research fills the gap by using firm-level data on environmental (and financial) performance and green research and development (R&D) investment. Our unique hand-collected dataset on Japanese firms enable us to investigate the association of green R&D (and R&D) with environmental (and financial) performance.

Increasing societal concerns over environmental degradation and the environmental externalities of business practices push corporate managers to reconsider their current business practices and look for ways to mitigate their firms' environmental impact (Porter and Reinhardt, 2007). Some common examples include environmental management systems, pollution prevention, reuse and recycling, energy efficiency, and carbon management. However, the fundamental question now facing corporate managers is how these activities and strategies to reduce environmental impacts affect business performance (McWilliams and Siegel, 2000; Menguc and Ozanne, 2005; Orlitzky et al., 2003; Lee and Min, 2014).

Over recent decades, debate has been ongoing as to the relationship between environmental innovation and business performance. While conventional wisdom holds that investing in environmental management increases costs without resulting in financial benefits (Palmer et al., 1995; Walley and Whitehead, 1994; Ambec and Lanoie, 2008), a new green perspective considers that early investments in environmental management offset operational costs and enhance financial returns in the long term (Porter and van der Linde, 1995; Aragón-Correa et al., 2008; Sambasivan et al., 2013). In recent years, the management literature has increasingly emphasized the idea of "win–win" environmental

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strategies, through which proactive environmental management will benefit environmental and economic performance. In business practice, however, developing environmentally friendly products (i.e., green products) while remaining economically and commercially competitive is a significant challenge (Lee and Ball, 2003; Lee and Kim, 2011). Meeting this challenge to create win–win strategies requires more empirical evidence that is applicable to business performance.

In many cases, manufacturing firms attempt to develop green products or production supported by increased operational and energy efficiency (Dangelico and Pujari, 2010). Environmental innovation (or eco-innovation) is a common environmental strategy that many firms adopt to achieve superior environmental and economic performance simultaneously (Dangelico and Pujari, 2010; Triguero et al., 2013). Eco-innovation is

> "the production, assimilation or exploitation of a product, production process, service or management or business methods that is novel to the organization (developing or adopting it) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources used (including energy use) compared to relevant alternatives (Kemp and Pearson, 2008, p. 7)."

Eco-innovations are strongly related to firms' investment in research and development (R&D). Importantly, the outcomes from eco-innovation are not immediately apparent, and firms need a long-term perspective on the innovation, particularly since "innovation cannot always completely offset the cost of compliance, especially in the short term before learning can reduce the cost of innovation based solutions (Porter and van der Linde, 1995, p. 100)." In general, the debate on the link between environmental (or eco-) innovation and firm performance has been inconclusive and lacking in consensus, indicating that the debate continues (Ghisetti and Rennings, 2014). More research on the impact of eco-innovation on firm performance is needed to provide a solid foundation that will encourage and guide corporate managers on how to achieve superior environmental and financial performance simultaneously.

In this research, carbon emissions serve as a proxy for environmental performance and green R&D as a proxy for eco-innovative R&D investment. The main objective of this study is to examine the relationship between green R&D investment and carbon emissions and the relationship between green R&D investment and firm's financial performance.

The remainder of this paper is organized as follows. First, a review of the literature on eco-innovation and its impact on firm performance within the resource-based view and the natural resource-based view establishes a foundation for hypothesis development. Next, description of the data and model to test the hypothesis is followed by presentation of the results and further analysis and subsequent discussion on the effects on financial performance. The final section offers conclusions and implications of the study's findings.

2. Theoretical foundation and hypothesis development

The resource-based view (RBV) and natural resource-based view (NRBV) provide an appropriate theoretical basis for discussing the contribution of resources and capabilities to the performance of eco-innovation (Menguc and Ozanne, 2005; Dangelico and Pujari, 2010; Lee and Kim, 2011). In particular, these theories shed light on the relationships among resources, capabilities, and performance, which constitute the basis for eco-innovation in a holistic view.

The RBV and NRBV essentially hold that the competitive advantage of a firm lies in heterogeneous resources that have the distinctive characteristics of being valuable, costly to imitate, and non-substitutable (Barney, 1991; Hart, 1995). Recognition that its resources by themselves are insufficient to create a competitive advantage raises the strategic importance of a firm's specific efforts or ability to exploit its resources to its own advantage. However, the RBV has been criticized as being unable to explain how to deploy resources to achieve a competitive advantage within a changing external environment (DeSarbo et al., 2005; Hart, 1995). In light of the currently changing institutional regulations, market pressure, and stakeholder influence related to the natural environment, the RBV has obvious limitations in explaining how to improve business performance relating to the natural environment. Furthermore, management theory, including the RBV, has ignored the constraints imposed by the natural environment, and "given the growing magnitude of ecological problems……. this omission has rendered existing theory inadequate as a basis for identifying important emerging sources of competitive advantage (Hart, 1995, p. 987)."

With the increasing environmental pressures from the government and marketplace, firms face sustainability challenges to fostering effective eco-innovation capabilities (Dangelico and Pujari, 2010; Cheng et al., 2014). Building on the concept of the RBV, Hart (1995, 2005) developed the NRBV by including natural environmentally caused constraints and opportunities and arguing that a sustainable competitive advantage can be achieved through valuable, rare, costly-to-copy, and immovable firm resources and capabilities of the firm. According to the NRBV, to respond to the natural environment and achieve long-term success, firms need to accumulate resources and manage capabilities with a longer-term focus rather than a short-term focus on profits at the expense of the environment. An ability to envision sustainable technologies and products can lead to a firm's competitive advantage in the market. Further elaboration of the NRBV highlighted the links between environmental strategies, green capabilities, and competitiveness at a firm level (Hart, 2005; Hart and Dowell, 2011).

As a part of a sustainable development strategy, eco-innovation can be viewed as the cultivation of distinctive, long-term focused green capabilities, buttressed by top management support, eco technologies, and R&D investment. External eco-innovation includes all green external activities of the firm, particularly those involving suppliers, government agencies, and market. Internal eco-innovation includes business practices for efficient and effective management of eco-innovation processes, particularly new product development (Cheng et al., 2014; Ghisetti and Rennings, 2014). While eco-innovation can be further defined in terms of products, processes, and organizations (Pujari et al., 2004; Lee and Kim, 2011; Triguero et al., 2013), this research adopts the definition of eco-innovation from Kemp and Pearson (2008), which highlights both the operational and organizational efforts of a firm to reduce negative environmental impacts. As a firm engages in eco-innovation and makes substantial efforts to reduce the negative effects of activities on the natural environment, many aspects of existing production, processes, and product development need to be reconsidered (Hart, 1995; Gonzalez-Benito and Gonzalez-Benito, 2005).

As a result of adopting eco-innovation, a firm's environmental performance may improve. A study of environmental management and environmental performance described environmental performance at the firm level as a measurement of how successful a firm is in reducing its negative impact on the natural environment (Klassen and McLaughlin, 1996; Gutowski et al., 2005). Environmental performance includes efficient use of resources, reduction of wastes and energy consumption, and reduction of environmental risks (Aragón-Correa et al., 2008). To improve environmental performance using eco-innovation, firms need to invest in new environmental technologies to reduce pollution and carbon emissions. Eco-innovation can help to identify inefficiencies in production and existing environmental technologies, to improve energy efficiency and at the same time lead to product innovations (Melynk et al., 2003; Porter and van der Linde, 1995; Sambasivan et al., 2013).

In addition, investment in environmental technologies to reduce pollution and carbon emissions requires redesign of production, and product development is expected to improve the operational level of performance, such as by lowering energy consumption and carbon emissions. Some scholars have found a positive relationship between environmental investment and operational performance (Gonzalez-Benito and Gonzalez-Benito, 2005; Klassen and Whybark, 1999). For example, research has shown a positive link between R&D expenditures and environmental management systems (Arora and Cason, 1996), but a negative link between R&D expenditures and pollution emissions (Cole et al., 2005). In the same vein, research has also found a positive link between proactive environmental management and environmental performance (López-Gamero et al., 2009). So far, the link between R&D investment and environmental performance seems to be quite blurred (Etzion, 2007; Padgett and Galan, 2010).

To adopt eco-innovation at a firm level, firms need to make a long-term commitment, mainly in the form of R&D investment for new environmental technologies (Roome, 1994). R&D activities on eco-innovation often center on the improvements of internal resources and capabilities to reduce environmental impacts. This study employs the term “green R&D,” which focuses on R&D activities for eco-innovation. When firms adopt eco-innovation with green R&D investment and activities, they attempt to improve productivity and efficiency and to reduce costs and environmental impacts. However, firms usually underestimate the economic benefits from pollution reduction (Hart, 1995, 2005; Hart and Ahuja, 1996; King and Lenox, 2002). This undervaluation can be driven by the costs associated with eco-innovation for sustainability, as firms can be unlikely to bear the full costs of eco-innovation, and thus can under-utilize green resources and capabilities. Incorporating eco-innovation into sustainable corporate strategy requires resolution of the conflicts between economic and environmental criteria by exploring new resource combinations and deploying existing resources for a sustainably better way (Hart, 1995; Sharma et al., 2007). Several studies have examined the relationship between environmental and firm performance (Ambec and Lanoie, 2008; Elsayed and Paton, 2005; Horváthová, 2010). Notably, a meta-analysis of 64 empirical studies between 1978 and 2008 showed that 55% of the studies found a positive, 15% a negative, and 30% an insignificant (or no) effect of environmental performance on economic performance (Horváthová, 2010). Despite an accumulation of empirical evidence over the last decade that eco-innovation and proactive environmental strategies are likely to produce positive impacts on financial performance, answers remain elusive.

In summary, therefore, green R&D investment for eco-innovation can help a firm develop unique resources and capabilities that can increase its eco-innovation and lead to superior environmental and financial performance. With a focus on green R&D and carbon emissions, the following hypotheses are advanced:

Hypothesis 1. *A firm's green R&D investment is positively related to carbon emissions (environmental performance).*

Hypothesis 2. *A firm's green R&D investment is positively related to financial performance.*

3. Data and model

Japanese methods of development in innovation and manufacturing still play an important role in new product development, production and operations in many developed and developing countries. An investigation of Japanese eco-innovation and green R&D management practices has important implications for green management. In particular, competitive advantage can be gained by the implementation of proactive environmental strategies which employ valuable resources and capabilities to minimize environmental impact and to increase operational efficiency.

Environmental performance data came from the Environmental Report Plaza, which is released by the Japanese Ministry of Economy, Trade and Industry. Financial data came from the Nikkei Economic Electronic Databank System (NEEDS). All variables used in the estimation are for Japanese manufacturing firms' annual data between 2001 and 2010. Table 1 reports that the mean value of carbon emission (divided by asset) is 2.09 with maximum value of 35.76. The reason why divided by asset is to minimise heterogeneity problem which arises from different size of firm. For example, the large size of firm the more emission of carbon dioxide. Asset is commonly used proxy for size of firm. During our sample period, carbon emission is the only available variable to use as a proxy for environmental performance at a firm level. Environmental performance could be broadly deduced from the perspective of sustainability, however this may require a large number of variables, including the measurement of pollutants and environmental capacity. Due to the limited availability of data, we focus on the emission of carbon as a proxy for environmental performance. One advantage of using carbon emissions, however, is that our research covers a firm's environmental performance, and this is directly associated with the most serious global environmental issue. Carbon dioxide emission is reported to be the most critical source of global warming. The 1997 Kyoto Protocol in promotes a decrease in carbon dioxide emissions and Japanese firms recognise that this decrease is the most important measure of environmental performance.

The total value of R&D is calculated by aggregating the values of Green_R&D and R&D. Green_R&D is a firm's expenditure on R&D, particularly aiming at environmental measures, while R&D is expenditure on generic R&D without specifying an environmental measure. Eco-innovation could be a firm's deliberately targeted efforts or a secondary effect of other business activities. The availability of reliable data at a firm level is the most important reason why we chose Green_R&D as a proxy for environmental innovation. In order to minimise the problem of heterogeneity, all R&D-related variables are scaled by sales values. Sales refer to total sales revenue, and this is regarded as being more associated with R&D than the size of a firm based on total assets. However, the untabulated table indicates that the estimation of R&D scaled by asset is consistent with our findings. Our two key independent variables are Green_R&D and R&D. The mean values of Green_R&D and R&D are 0.88 and 8.17, respectively. However, mean values sometimes fail to describe data distribution when outliers exist. The inter-quartile value is obtained by the difference between the 25th and 75th percentiles. The term inter-quartile is widely used to describe where the bulk of samples lie, and the spread between the largest and smallest of the middle half of the data. The calculated inter-quartile values of the two variables are 0.59 and 5.34, respectively. This indicates that the bulk of both Green_R&D and R&D values lie to the left hand side of the mean values, possibly due to some firms' heavy expenditure on Green_R&D and R&D. We therefore estimated our results using the log value of these variables as an alternative, but found similar results (not reported). Energy_Intensive is an indicator variable equal to 1 if a firm belongs to an energy-intensive industry and 0 otherwise. The energy-intensive sector includes the chemical, steel, metals, pulp and paper, and utilities industries. Mean value of Energy_Intensive implies

Table 1
Summary statistics.

Variable	Number of firm-year observation	Mean value	Median value	Standard deviation	75th percentile	25th percentile	Minimum value	Maximum value
CO_2(carbon dioxide)	2942	2.09	0.57	4.41	1.55	0.23	0.00	35.76
R&D_total	1562	7.63	4.38	17.51	7.58	1.61	0.03	369.40
Green_R&D	1842	0.88	0.20	5.33	0.64	0.05	0.00	190.92
R&D	944	8.18	4.22	20.20	7.12	1.77	−8.75	360.01
Energy_Intensive	3580	0.57	1.00	0.49	1.00	0.00	0.00	1.00
Capital intensity	3453	1.89	1.27	3.68	1.66	0.98	0.23	56.86
Firm size	3467	12.02	11.95	1.38	12.83	11.17	7.25	17.65
Leverage	3446	50.05	50.05	20.06	66.47	36.02	1.67	125.89
Tobin's Q	3275	1.30	1.15	0.60	1.44	0.97	−3.34	7.88

Definitions and descriptions of variables: CO_2 is calculated by CO_2/asset in percentage. R&D_total, Green_R&D and R&D are calculated by Green_R&D/sales and R&D/sales. Energy_Intensive is an indicator equal to 1 if a firm belongs to an energy-intensive industry and 0 otherwise. Capital intensity is defined as asset/sales. Firm size is calculated by the natural logarithm of sales. Leverage is defined as debt/(debt + equity). Tobin's Q is calculated by (book value of asset + market value of equity)/book value of asset. The reason why mean values are outside of the low and high quartile is because of the skewness. The reason why 'mean' values of R&D_total look different from the 'mean' values of Green_R&D and R&D is because of the different number of observations.

around 57% of sample belongs to an energy-intensive industry. We calculated Tobin's Q by (book value of asset + market value of equity)/book value of asset. Tobin's Q is widely used to measure a firm's value (Demsetz and Lehn, 1985), while a firm's accounting performance is subject to changing accounting principles. Tobin's Q is also a theory-based (but relatively easy to calculate) variable and it reflects the market evaluation of a firm's performance (Hayashi, 1983). The reason why scaled by (book-value) asset is that asset is widely used as a proxy for the replacement costs of physical assets (Demsetz and Lehn, 1985). The mean value of the Tobin's Q is 1.3 which exceeds the unity, implying that on average, Japanese firms' profits are greater than the costs of their assets. This suggests that the evaluations carried out during our sample period show the affordability of investment by Japanese firms, and their market values are increased.

Table 2 reports the correlation matrix among variables. A pairwise correlation is calculated by the covariance between the pairwise variable scaled by standard deviations of the two variables. Carbon emissions (CO_2), our outcome variable, has negative correlations with R&D_total and Tobin's Q but a positive association with Energy_Intensive, Capital Intensive, Firm Size and Leverage. The negative correlation between carbon emissions and R&D variables is as expected, although the statistical significance only exists for R&D_total. Despite the statistical significance, the magnitude of the correlation between carbon emission and R&D_total seems to be relatively low. However, this should not be of concern, because the pair-wise correlation shows only the relationship between the two variables, rather than the causal relationship. In particular, the calculated correlation will be confounded when there is a third variable affecting both the movements of the variables and its mean values simultaneously. As such, we need to control for any possible third factors in order to clarify the relationship between the two variables. Green_R&D has a negative association with Energy_Intensive and Firm Size but a positive correlation with R&D, Capital Intensive and Leverage. Like Green_R&D, R&D has negative association with Firm Size, but the negative association with Energy_Intensive is not statistically significant. As we described above, the correlation between CO_2 and R&D_total could be confounded by a third factor, and therefore we will address this issue in detail using regression analysis. The benefit of regression analysis is that the estimated coefficient shows the marginal effect of a variable on the outcome variable, controlling for possible confounding variables. Green_R&D has a positive association with R&D, Capital Intensive, and Leverage whereas R&D has a positive correlation with Green_R&D and Capital Intensive.

3.1. Estimation model

The restricted model is:

$$Y_{it} = cons\tan t + \beta_1 Green\_R\&D_{it} + \beta_2 R\&D_{it} + \beta_3 Green\_R\&DXR\&D_{it} + \varepsilon_{it}$$

Y_{it} is the outcome variable which could be either carbon emissions or financial performance. Carbon emission is used to investigate hypothesis 1, and financial performance is used to examine hypothesis 2. i and t respectively denote firm and year. Our main independent variable is Green_R&D and hypotheses 1 and 2 suggest that the estimated coefficient of β_1 is positive. Green_R&D X R&D is an interaction variable generated by the multiplication of

Table 2
Correlation matrix.

	CO_2	R&D_total	Green_R&D	R&D	Energy intensive	Capital intensive	Firm size	Leverage
CO_2	1							
R&D_total	−0.06[a]	1						
Green_R&D	−0.01	0.58[a]	1					
R&D	−0.04	0.99[a]	0.47[a]	1				
Energy_Intensive	0.30[a]	−0.07[a]	−0.07[a]	−0.05	1			
Capital Intensive	0.05[a]	0.66[a]	0.47[a]	0.68[a]	0.04[a]	1		
Firm Size	0.10[a]	−0.19[a]	−0.18[a]	−0.23[a]	−0.06[a]	−0.31[a]	1	
Leverage	0.26[a]	−0.06[a]	0.05[a]	−0.05	0.02	0.01	0.23[a]	1
Tobin's Q	−0.10[a]	0.04	0.01	0.03	−0.10[a]	−0.02	0.13[a]	−0.16[a]

[a] Indicates significance at the 5% level. Our null hypothesis for a two-tailed test is absence of correlation between two variables. Statistical significance (not significance) at 5 percent level refers to a sample evidence which allows us to reject (cannot reject) the null hypothesis with the probability of type I error of 5 percent (i.e., $\alpha = 0.05$). Figures in table are pairwise correlation, calculated by $\sum_{i=1}^{n}(x_{1i}-\bar{x}_1)(x_{2i}-\bar{x}_2)/\sqrt{\sum_{i=1}^{n}(x_{1i}-\bar{x}_1)^2}\sqrt{\sum_{i=1}^{n}(x_{2i}-\bar{x}_2)^2}$, where $\bar{x}_.$ refers to mean value. In calculation, missing values are not used. For example, the correlation between CO_2 and R&D_total is calculated by the obtained mean value, covariance and then standard deviations using only observed values.

Green_R&D with R&D. The R&D variable captures a firm's expenditure and is aimed at generic R&D, such as improving/creating new technology rather than directly targeting a reduction in environmental emissions. An assumption of this restricted model is that variations arising from other (omitted) variables than Green_R&D and R&D variables are well-behaved. Namely, the variations are included as part of residuals which will be zero on average. As we described above in Table 2, however, confounding effects through omitted variables may bias the estimatedβ_1.

A firm's environmental and financial performance can also be influenced by non-R&D factors. For example, firm's energy intensiveness (and capital intensiveness) could be associated both with Green_R&D and environmental performance. Size of firm (and leverage) can also have correlations with Green_R&D and financial performance. To minimise any estimation bias due to an omitted variable, therefore we include other control variables in the following unrestricted model:

$$Y_{it} = cons\tan t + \beta_1 Green\_R\&D_{it} + \beta_2 R\&D_{it} + \beta_3 Green\_R\&DXR\&D_{it} + Others + \varepsilon_{it}$$

where *Others* include observed control variables, such as firm size, leverage, capital intensiveness and a binary variable for energy intensiveness. To examine estimation bias due to unseen omitted variables, an interaction variable and a year-industry variable are included. The year-industry variable 1xJT is a vector of binary variables, where J is 2-digit Japanese Standard Industry Classification and T is the total number of years (i.e., 10). The year-industry effect is expected to capture the effect of time-varying at industry level on carbon emissions or on financial performance. For example, changes in yearly-based outputs at industry level which is caused by business cycle can affect environmental performance. The magnitude of this affect is a function of the change in energy intensiveness of firm when industry outputs change. As such, we need to control for this (unobserved) effect by including the year-industry interaction variable. Otherwise, the estimated coefficients are subject to the estimation bias due to omitted variables. In a similar vein, changes in outputs at industry level affect financial performance. The included year-industry interaction variable is expected to control for variations arising from this change in yearly-based outputs. That means the estimated coefficient β_1 is obtained from the variations within an industry at a particular year of time. The effects of exchange rate movements, as macroeconomic shocks on firms, usually differ depending on the industry. Therefore, a year-industry variable is expected to control for the effect of industry-level time-varying (macro) fixed effects in an estimation of the firm's performance model.

We estimate coefficients using the STATA (v.12) software which uses the minimum mean square linear predictor (least square linear predictor). The coefficient is estimated by: $\widehat{\beta} = \sum_{i=1}\sum_{t=1}\mathbf{x}'_{it}\mathbf{x}_{it} / \sum_{i=1}\sum_{t=1}\mathbf{x}'_{it}Y_{it}$, where $\mathbf{x}$ refers to a vector of independent variables. The Huber-White method for heteroskedasticity-robust standard error for the estimation coefficients is calculated by (Wooldridge, 2010): $\widehat{V}[\widehat{\beta}] = \sum_{i=1}\sum_{t=1}\mathbf{x}'_{it}\mathbf{x}_{it}\widehat{\boldsymbol{\varepsilon}}^2_{\mathbf{it}} / [\sum_{i=1}\mathbf{x}'_{it}\mathbf{x}_{it}]^2$, where $\widehat{\varepsilon} = Y_{it} - \mathbf{x}'_{it}\widehat{\boldsymbol{\beta}}$ is the Ordinary Least Square residual.

4. Estimation results

Table 3 reports estimation results with different model specifications for sensitivities checks. Estimation results in Columns 1 and 2 report that both Green_R&D and R&D negatively affect carbon emissions but only Green_R&D is statistically significant. The positive effect of Green_R&D is consistent with Hypothesis 1. These results also imply that the inclusion or exclusion of industry-level fixed effects is without much difference in terms of magnitude of estimated coefficients. Effects in Columns 3 and 4 include interaction between Green_R&D and R&D. The results show that the positive effect of green R&D investment on environmental performance is attenuated by an increase in R&D expenditure. This result implies that the estimated sign of this variable is negative and statistically significant. This finding also implies that the negative effects of Green_R&D on carbon emissions are attenuated when a firm increases its R&D for non-environmental innovation. Intuitively, an increase in output resulting from non-green R&D can exacerbate environmental performance. To confirm this conjecture, another interaction variable is included by multiplying a binary variable for energy-intensive industry by this Green_R&D X R&D variable (Columns 5 and 6).

Observation of the attenuated interaction effects between Green_R&D and R&D in Columns 3 and 4 led to examination for any difference between energy-intensive and other industries. Energy_Intensive in Columns 5 and 6 are binary variables, indicating 1 when firms belong to an energy-intensive industry and 0 otherwise. As expected, the estimated coefficient of Energy_Intensive is positive and significant at the 1% level. The positive sign of the doubled multiplication, Green_R&D X R&D X Energy_Intensive, suggests that the attenuating effect of Green_R&D X R&D is intensified in energy-intensive industries compared to other industries. That is, an increase in outputs by non-Green R&D in energy-intensive industries naturally leads to poorer environmental performance.

5. Further analyses

5.1. Economic effect of R&D and green R&D on carbon emissions

The result in Table 3 (Column 3) indicates that, when R&D takes its mean value of 8.18 as reported in Table 1, the marginal effect of an increase in a one inter-quartile of Green_R&D (=0.59) on the ratio of carbon emission to asset is −0.095. This is equivalent to approximately a 4.5% reduction of mean value of carbon emission (scaled by asset).

However, Graph 1 illustrates that this reduction effect of increase in one inter-quartile Green_R&D is diminishing as a firm increases its R&D expenditure. For example, the marginal effect of one inter-quartile Green_R&D on carbon emission is −0.09 when R&D increases by a one inter-quartile range (=5.348) from its mean value of 8.178. This reduction is equivalent to 4.3% of mean value of carbon emission (scaled by asset).

Looking at the impact of a one inter-quartile increase in R&D (=5.348) on the mean value of Green_R&D (=0.889) is another way to characterize these economic effects.

As shown in Graph 2, considering that the R&D and Green_R&D variables are de-meaned, a marginal effect of CO_2 by an increase of one inter-quartile in R&D when firms take their mean value of Green_R&D (=0.89) is affected solely by R&D because the interaction variable becomes annihilated. Thus, the marginal effect of an increase of one inter-quartile in R&D when Green_R&D takes its mean value is −0.096. This is the equivalent of 4.6% of mean value of carbon emissions (scaled by asset) and slightly smaller than that (=5%) by an increase of one inter-quartile in Green_R&D when R&D takes its mean value.

However, this dynamic is attenuated as firms' Green_R&D increases. When a firm increases its Green_R&D one inter-quartile range from its mean value (1.49 = 0.89 + 0.59), the marginal effect on CO_2 is −0.089. This is equivalent to 4.25% of mean value of carbon emissions (scaled by asset).

Table 3
Effects of Green_R&D and R&D on carbon emissions.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Green_R&D	−0.061**	−0.052**	−0.176***	−0.314***	−0.116**	−0.204***
	[0.016]	[0.032]	[0.000]	[0.000]	[0.010]	[0.000]
R&D	−0.004	−0.005	−0.018*	−0.041***	−0.023***	−0.034***
	[0.634]	[0.565]	[0.071]	[0.003]	[0.005]	[0.006]
Green_R&DXR&D			0.002***	0.003***	0.002***	0.003***
			[0.002]	[0.000]	[0.001]	[0.000]
Energy_Intensive					4.362***	3.850***
					[0.000]	[0.000]
Green_R&DXR&DXEnergy_Intensive					0.002***	0.002***
					[0.000]	[0.000]
Capital intensity				0.206***		0.140***
				[0.000]		[0.000]
Firm size				0.513***		0.443***
				[0.000]		[0.000]
Leverage				0.046***		0.034***
				[0.000]		[0.000]
Year-industry effect	No	Yes	Yes	Yes	Yes	Yes
_cons	1.905***	2.385***	2.023***	−6.768***	−3.006***	−9.541***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
N	936	936	936	936	936	936
R2_a	0.001	0.003	0.009	0.098	0.157	0.207

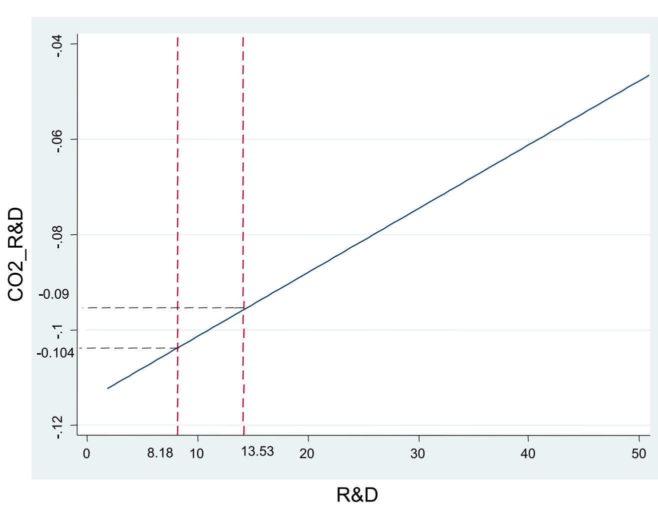
Dependent variable is CO_2 scaled by asset. Numbers in [ ] are Huber-White adjusted *p*-values. R&D_total is sum of Green_R&D and R&D and all R&D related data are mean-centred. Capital intensity is proxied by Asset scaled by sales. Firm size is proxied by sales in natural logarithm. Leverage is defined as Debt divided by (Debt plus Equity). Energy intensive is a binary variable. R2_a refers to adjusted R-square.
*, **, *** refers to significance at the 10, 5, and 1% level respectively.

In summary, results show that the marginal reduction effect of Green_R&D on CO_2 emission when firms take mean value of R&D is 5% and this is slightly greater than the marginal reduction effect of R&D when firms take the mean value of Green_R&D. Results also show that the dynamic marginal reduction effect of Green_R&D (R&D) is diminishing as firms increase R&D (Green_R&D) values.

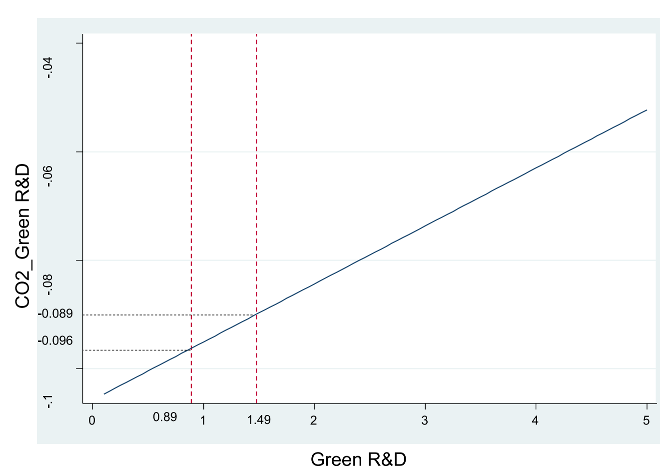
5.1.1. *Effects on financial performance*

The results in Column 1 in Table 4 report that the estimated coefficients of both Green_R&D and R&D have a positive association with Tobin's Q. As this finding illustrates, the positive effects of Green_R&D on firm value are robust even when we control for firms' expenditure on generic (i.e., non-environmental) R&D. Note that Green_R&D, R&D and its interactive variables are mean-centred. These mean-centred variables do not affect the estimated coefficients and standard errors, but only affect the constant value. That is, the value of 1.528 in Column 1 implies that the estimated population firm value (Tobin's Q) is 1.528 when Green_R&D (and R&D and the interaction variable) has its mean value. In contrast the interaction between these two variables, Green_R&D x R&D, has a negative sign, implying the attenuated positive effects of the two variables. For example, the positive effects of Green_R&D on Tobin's Q is attenuated as a firm increases its (generic) R&D expenditure. This finding is almost symmetrical with the results of the benchmark estimation (Column 3) in Table 3 above. As expected, results in Column 2 report that carbon emission decreases the firm's Tobin's Q value.

These findings are robust irrespective of model specifications from Column 3 to Column 6, although the magnitude of estimated coefficients varied somewhat. Considering the measurement of Tobin's Q, book value of assets plus market value of equity divided by book value of assets, the finding implies that the market investor values positively the firm's Green_R&D and R&D expenditure. For example, as the result in Column 1 indicates, in a hypothetical world where a firm's R&D takes its mean value, the effect of an



Graph 1. Marginal effect line of CO_2 to a one inter-quartile change in Green_R&D at different levels of R&D.



Graph 2. Marginal effect line of CO_2 to a one inter-quartile change in R&D at different levels of Green_R&D.

Table 4
Effects of Green_R&D, R&D and carbon emissions on Tobin's Q.

	Tobin's q (Model 1)	Tobin's q (Model 2)	Tobin's q (Model 3)	Tobin's q (Model 4)	Tobin's q (Model 5)	Tobin's q (Model 6)
Green_R&D_C	0.035**		0.033*	0.095***	0.030*	0.087***
	[0.045]		[0.056]	[0.000]	[0.085]	[0.000]
R&D_C	0.004***		0.004***	0.011***	0.005***	0.012***
	[0.000]		[0.000]	[0.000]	[0.001]	[0.000]
Green_R&DXR&D_C	−0.001***		−0.001**	−0.001***	−0.001***	−0.001***
	[0.001]		[0.001]	[0.000]	[0.001]	[0.000]
CO_2		−0.014***	−0.013***	−0.009***	−0.008**	−0.010**
		[0.000]	[0.000]	[0.004]	[0.041]	[0.011]
Energy_Intensive					−0.152***	0.106**
					[0.008]	[0.047]
Green_RDXRDXEnergy_Intensive					0.001*	0.001*
					[0.087]	[0.057]
Capital intensity				−0.029***		−0.029***
				[0.000]		[0.000]
Firm size				0.092***		0.082***
				[0.000]		[0.000]
Leverage				−0.006***		−0.007***
				[0.000]		[0.000]
Year-Industry effect	Yes	Yes	Yes	Yes	Yes	Yes
_cons	1.528***	1.340***	1.565***	0.742***	1.730***	0.598***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.001]
N	903	2773	896	896	896	896
R2	0.033	0.01	0.04	0.112	0.047	0.09
R2_a	0.029	0.01	0.035	0.104	0.04	0.081

Note: Number of firm-year observations vary due to missing values particularly for R&D related data.

increase in one inter-quartile range of Green_R&D (=0.59) is around 2.0%. This 2% is equivalent to 1.54% of (average) Tobin's Q values. However, this dynamic is attenuated as a firm raises its R&D increases more than its mean value. For example, as a firm increases one inter-quartile value of R&D from its mean value, the marginal effect of increase in one inter-quartile of Green_R&D on Tobin's Q drops from 2.0% to 1.7%.

Similarly, in a hypothetical world where a firm's Green_R&D takes its mean value, the effect of an increase in a one inter-quartile range of R&D (=5.348) is 2.1%. However, as a firm increases one inter-quartile value of Green_R&D from its mean value as well, the marginal effect of an increase in one inter-quartile of R&D on firm performance drops from 2.1% to 1.8%.

6. Conclusions

The RBV and NRBV allow analysis of the effect of R&D, in particular the effect of green R&D investment, on environmental and financial performance. As discussed previously, a firm's environmental performance and R&D possess characteristics of both the RBV and the NRBV, making them key resources that will allow a firm to achieve superior environmental and financial performance. Given the importance of these resources to a firm's performance, recent studies claim that R&D must be included to accurately measure how corporate social responsibility affects a firm's economic performance. This investigation adopted both R&D and green R&D for eco-innovation. Since existing studies have not provided a clear distinction between R&D and green R&D, measuring the relationship between R&D and eco-innovation is difficult. That is, how general R&D made a signification contribution to environmental and financial performance is very unclear. Thus, with the aim of giving better explanations for the link between green R&D and carbon emissions, this research focuses on green R&D, which specifies R&D activities for eco-innovation in product, process, and operational efficiencies.

The results confirm that a firm's green R&D investment decreases carbon emissions and increases firm value, measured by Tobin's Q. Therefore, findings support the presence of a negative relationship between green R&D investment and carbon emissions. At the same time, green R&D is positively related to financial performance at the firm level. Notably, firms accumulate valuable resources and capabilities for superior firm performance. This study confirms that green R&D contributes simultaneously to superior environmental performance (carbon emission reductions) and financial performance (Tobin's Q). This finding explicitly supports the need for unique organizational resources and capabilities to buttress a proactive environmental strategy. These resources and capabilities in turn make contributions for competitive advantage.

The contributions of this study are three-fold. Firstly, the study uses carbon emissions and green R&D data as proxies for environmental performance and eco-innovation at the firm level, with resulting unique datasets of Japanese manufacturing firms between 2001 and 2010. While the extensive use of industry-level proxies, such as patents, contributes to ambiguity in measurement, this practice has arisen mainly because of the limited availability of data at the firm level. However, industry-level data fail to reflect firms' strategic decisions on allocation of resources for the development of eco-technologies. In contrast to data in existing studies, the micro firm-level datasets in this study allow a more reliable examination of the relationship between green R&D and environmental and financial performance.

Secondly, this study's empirical results are expected to contribute to the existing controversial debate on the issues, especially as the link between R&D investment and firm's environmental and financial performance has been controversial rather than conclusive. Our results show the presence of a negative relationship between green R&D and carbon emissions while green R&D is positively related to financial performance at the firm level. Our findings explicitly support that there is a need for corporate management to engage unique organizational resources and capabilities in order to adopt a proactive environmental strategy for superior corporate environmental and financial performance. Thirdly, the sample of Japanese manufacturing firms offers important insights into the research topic because most prior firm-level studies focus on U.S. (United States) industries. The ready generalization of learning outcomes from Japan about innovation and manufacturing over the decades testifies to the value of investigating how Japanese manufacturing companies face and manage environmental challenges—particularly carbon emissions—through green R&D and eco-innovation. As a scarcity of natural resources and land space require Japanese manufacturing firms to balance environmental and economic performance by achieving low-carbon emissions, the case of Japan offers important implications for carbon-constrained economies in Asia, Europe, and other regions.

There are some limitations to this study, which could lead to further studies and recommendations for future directions. Firstly, the study's focus is on green R&D investment that a firm makes for eco-innovation, which aims at reducing environmental impacts in product, process, and operational efficiencies. This focus limits the study's sample to manufacturing industries in which green R&D is a significant proportion of total R&D. Therefore, the study's findings are not readily applicable to non-manufacturing industries that have little green R&D activity, and some caution should be exercised in generalizing the findings across different industries and firms. More research is needed to generalize the findings of this study across industries and nations. In order to increase the validity of this study, future studies should pay more attention to both manufacturing and non-manufacturing industries by conducting comparative studies in emerging, developing and developed countries. Secondly, the study relies on Japanese manufacturing firms because the Japanese sample during the period of 2001–2010 provides different insights on eco-innovation and green R&D. Since green R&D is likely to be affected by national environmental regulations and policies as well as market pressures, researchers should be cautious when attempting a comparison with other countries. Recommendations for future research should be directed at broadening the model to further consider important variables such as the global economic crisis and national environmental regulations. Therefore it is recommended that researchers conduct studies on both one single country and a comparative global study using local institutional factors such as selected time periods, national environmental policies and market pressures.

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