Complex supply chain structures and multi-scope GHG emissions: The moderation effect of reducing equivocality

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Purpose – Climate change requires the reduction of direct and indirect greenhouse gas (GHG) emissions, a task that seems to clash with increasing supply chain complexity. This study analyses the upstream supply chain complexity dimensions suggesting the importance of understanding the information-processing that these may entail. Reducing equivocality can be an issue in some dimensions, requiring the introduction of written guidelines to moderate the effects of supply chain complexity dimensions on GHG emissions at the firm and supply chain level.

Design/Methodology/Approach – A three-year panel data was built with information obtained from Bloomberg, Trucost, and Compustat. Hypotheses were tested using random effect regressions with robust standard errors on a sample of 394 SP500 companies, addressing endogeneity through the control function approach.

Findings – Horizontal complexity reduces GHG emissions at the firm level, whereas vertical and spatial complexity increase GHG emissions at the firm and supply chain level. Although the introduction of written guidelines neutralises the negative effects of vertical complexity on firm and supply chain GHG emissions, it is not sufficient in the presence of spatial complexity.

Originality – This paper offers novel insights by suggesting that managers need to reconcile the potential trade-off effects on GHG emissions that horizontally complex supply chain structures can present. Their priority in vertically and spatially complex supply chain structures should be to reduce equivocality.

Keywords: Climate change, complexity, equivocality, GHG emission scopes, supply chain, structure, uncertainty.

Paper type: Research paper

1. Introduction

Complexity in the modern and global supply chains is one of the most critical problems in today's business context. Several market uncertainties drive companies to manage a certain level of supply chain complexity in order to carry out business strategies, which are key for their competitiveness (Aitken *et al.*, 2016; Chand *et al.*, 2022). However, paradoxically, supply chain complexity seems to get bad press in business (Reeves *et al.*, 2020) and the same market dynamics now require firms to aim for *decomplexity* in order to be competitive (Perona, 2023). Studies also show the negative effects of complexity on performance, associating them with increasing coordination costs, and a loss of visibility and control over suppliers (Busse *et al.*, 2017; Carter *et al.*, 2015; Choi and Krause, 2006; Kim and Davis, 2016; Lu and Shang, 2017; Meinlschmidt *et al.*, 2016; Wiengarten *et al.*, 2017).

Although the deleterious performance impact of supply chain complexity seems to be well-established in the literature (Turner *et al.*, 2018), there is an increasing body of studies that also argue a positive, or at least a balanced, impact of complex supply chains on performance (Adhikary *et al.*, 2020; Birkie *et al.*, 2017; Kim *et al.*, 2020; Sharma *et al.*, 2020). Hence, the literature on supply chain complexity remains inconclusive mainly because there are no converging theoretical arguments on how it affects performance (Akhavan and Zvezdov, 2021; Ateş *et al.*, 2022). Besides, supply chain complexity is differently conceptualised and operationalised, making it hard to compare findings (Ateş *et al.*, 2022; Chand *et al.*, 2022). The main gaps in the literature are related to a strong focus on performance at the firm or business unit-level and scarce approaches linking supply chain complexity to sustainability (Macchion *et al.*, 2020). An internal perspective on performance is clearly insufficient, especially for international companies, and more holistic approaches that consider performance at the supply chain or system level are now needed (Mahapatra *et al.*, 2021). Moreover, the increasing social concern about climate change requires in-depth study of the relation between supply chain complexity and sustainability, which is hinted at in the literature (Macchion *et al.*, 2020). The still predominant logic of pressure exerted by the focal firms on suppliers to achieve sustainability does not work in the presence of supply chain complexity, where structural dynamics must be considered in order to understand the impact of complexity on sustainability (Cole and Aitken, 2020; Gruchmann, 2022).

The aim of this study is to propose a more comprehensive theoretical and empirical assessment of the impact of supply chain complexity on GHG emissions by embracing the idea that emission scopes matter. Increasing market pressures now urge companies to help solve the problem of climate change by reducing GHG emissions derived not only from companies' production activities (so-called direct emissions), but also from the delivery of products and services (so-called indirect emissions) (Cadez *et al.*, 2019; Eggert and Hartmann, 2021). In fact, recent data and empirical evidence indicate that a significant amount of GHG emissions is indirect (Dahlmann and Roehrich, 2019; Gopalakrishnan *et al.*, 2021; IPCC, 2022), making it imperative to move towards more supply chain strategic approaches that actively manage GHG emissions not only at the firm but also at the supply chain level. This work incorporates both perspectives and examine how supply chain complexity affects focal firm and supply chain GHG emissions at the same time.

By using the lens of the organisational information-processing theory (OIPT) (Daft and Lengel, 1986; Galbraith, 1974), this study relies on the idea that at the firm level, some degree of complexity in the supply chain is inevitable and even desirable for being competitive (Wiengarten *et al.*, 2017). However, firms may face some potential negative effects on performance coming from a certain amount of complexity and even absorb or accommodate these effects as a part of their overall business strategy (Aitken *et al.*, 2016). In particular, we argue that upstream supply chain complexity, analysed under its multiple structural dimensions (i.e., horizontal, vertical, and spatial), works as a suitable vehicle to obtain a large and varied amount of information. From a strategic perspective, at the firm level, we consider that the processing of this information can be useful to reduce the focal firms' GHG emissions. However, after a certain point, some complexity dimensions may produce dysfunctional effects. At the supply chain level, complexity can embed high information-processing barriers that inhibit the possibility of reducing GHG emissions at different levels of the supply chain (Akhavan and Zvezdov, 2021; Pederneiras *et al.*, 2022). In both cases, we attribute the inability to achieve lower GHG emissions to the presence of equivocality. This can occur when the information being shared is confusing or ambiguous, and the risk is that misinterpretation of firms and along the supply chain can affect the correct execution of tasks and, consequently, performance. In this study, the reduction of equivocality is proposed as a salient issue that needs to be addressed to achieve lower GHG emissions, particularly at the supply chain level. To that end, we examine how the use of written guidelines, as a formal mechanism implemented by the focal firms, moderates the relationship between upstream supply chain complexity and GHG emissions reduction.

Our study makes several contributions. First, we extend the literature that examines the effects of supply chain complexity on performance. Differently from prior research, we use OIPT to better understand how complex supply chain structures affect GHG emission performance at both the firm and supply chain level. In doing so, we also strengthen the link between supply chain complexity and sustainability, providing a more nuanced understanding of how supply chain complexity fundamentally considerated at the firm level can impact on supply chain sustainability. We suggest the need for a change of perspective. Supply chain complexity has to be rethought under a more holistic view. If it is only considered from a corporate perspective, trade-offs in reducing GHG emissions can produce. We also contribute to the sustainable supply chain management literature by drawing attention to the importance of reducing equivocality through formal mechanisms such as written guidelines. Finally, we contribute to the incipient line of research that uses collective performance measures and improves the current knowledge of the dynamic effects that the different upstream complexity dimensions can have on GHG emissions reduction by using a panel data set and Scopes 1, 2 and 3 emissions as defined by the GHG Protocol.

2. Literature Review

2.1 Supply chain complexity perspectives

Supply chain complexity, defined by the complex adaptive system (CAS) literature as a large number of parts that interact in a non-simple way to react to changes in the environment (Choi *et al.*, 2001), has been studied under multiple perspectives.

A first perspective distinguishes between analyses at firm- or system-level (Aitken *et al.*, 2016). Under a firm point of view, supply chain complexity can be strategic or dysfunctional. Strategic complexity is required to carry out some business actions to obtain competitive performance. Therefore, it must be absorbed or accommodated by companies because it is intrinsically a part of their overall strategy. Dysfunctional complexity, on the other hand, is a supply chain complexity that is not needed to carry out firms' strategies and, if not reduced, prevents organisations from achieving a higher level of performance (Aitken *et al.*, 2016). Thus, under a firm-level perspective, managers should know the nature of complexity of their supply chain and consequently respond to obtain beneficial performance (Turner *et al.*, 2018). In turn, the CAS literature introduces a system-level perspective of supply chain complexity, suggesting that its effective management requires more comprehensive assessments (Choi *et al.*, 2001). At system-level, the management of supply chain complexity cannot be based on controlling, planning, and mapping activities carried out by an individual entity. Responses to supply chain complexity should involve organic interventions such as the adoption of shared interpretive and behavioural schema, and more formal mechanisms (Choi *et al.*, 2001). In this study, we consider both perspectives to understand how supply chain complexity affects performance either at firm or supply chain level.

Supply chain complexity has also been studied under a structural and dynamic perspective. The first one considers the number and variety of elements composing the supply chain system, and the second one considers how the multiple elements defining the supply chain system interact (Bode and Wagner, 2015; Bozarth *et al.*, 2009). The literature also distinguishes between internal (operational) and external (upstream and downstream) supply chain complexity (Bozarth *et al.*, 2009). Upstream complexity is associated with the size of the supply base managed by the focal firms and involves dynamics such as long supplier lead times and supplier delivery unreliability. Operational complexity is related to the complexity of products (e.g., variety and number of products) and their production processes. Finally, downstream complexity refers to the number and variety of customers in the supply chain and considers the dynamics related to demand variability (Bozarth *et al.*, 2009; Chand *et al.*, 2022). At the level of upstream complexity, then Choi and Hong (2002) define three dimensions of the supply chain complexity: horizontal, vertical, and spatial. Horizontal complexity is associated with the number of ties directly managed by the focal firms, vertical complexity with the number of levels in the chain, and spatial complexity with the geographical dispersion of the suppliers.

Although structural and dynamic aspects of complexity are strictly interrelated and are both relevant in the supply chain literature, the scope of this study focuses on structural supply chain complexity and specifically on upstream complexity where the majority of GHG emissions occur (Eggert and Hartmann, 2021). Besides, to offer a deep analysis of the effects of supply chain complexity on GHG emissions, we also consider the three dimensions of structural supply chain complexity introduced by Choi and Hong (2002).

2.2 Supply chain complexity and performance

The literature makes clear that supply chain complexity can impact performance directly either at the firm or supply chain level. At the firm level, studies analyse the effects of supply chain complexity on innovation (e.g. Ateş *et al.*, 2022; Kim *et al.*, 2020; Sharma *et al.*, 2020), financial, operational (e.g. Ateş *et al.*, 2022; Bozarth *et al.*, 2009; Lu and Shang, 2017) and environmental performance (Adhikary *et al.*, 2020). In contrast, at the supply chain level, the analysis of the impact of complexity on performance is more limited and focus on performance such as supply chain disruptions (Bode and Wagner, 2015; Brandon-Jones *et al.*, 2015), collective information disclosure (Gualandris *et al.*, 2021), operational performance (Blome *et al.*, 2014; Chand *et al.*, 2022) and the adoption of sustainability practices (Macchion *et al.*, 2020). Most of these studies tend to argue that supply chain complexity is detrimental on performance. The main arguments are that when complexity increases, the relationships between partners in the supply chain tend to become opaque, , preventing the possibility of improving performance (Kim and Davis, 2016). Besides, complex supply chains could involve more unreliable suppliers, imposing increasing coordination and administrative tasks and higher risks of supply chain disruptions (Bode and Wagner, 2015). At operational level, then, supply chain complexity is associated with numerous planning activities and a high need for resources that increase manufacturing costs (Bozarth *et al.*, 2009). The same arguments are also used to justify negative moderation effects of complexity on performance (Chowdhury *et al.*, 2023; Gruchmann, 2022; De Stefano and Montes-Sancho, 2018).

Recently, however, there is an increasing body of research that provides a positive, or at least balanced, perspective on how complex supply chains affect performance. As Reeves et al. (2020, p. 1) observe "*it can be cognitively demanding to understand how a system or organisation made up of many very different interconnected elements actually works. But the fact that such systems or organisations are difficult to understand doesn't make them inherently bad, especially in dynamic and uncertain environments where complexity can confer critical benefits*". Under this perspective, Birkie et al. (2017) verify that complexity in the supply chain has positive effects on the recovery of operations after disruptions, making supply chain resilience effective on performance. Kim et al. (2020) show that a greater number of direct ties with suppliers can effectively improve the innovation performance of focal firms, whereas Ateş and Memiş (2021) find positive effects of complexity on purchasing performance. Moreover, other studies argue that the positive effects coming from a complex supply chain structure can persist up to a certain point and then they may reduce (Lu and Shang, 2017; Sharma *et al.*, 2020). More specifically in the field of sustainability, Macchion et al. (2020) make it clear that the adoption of sustainability practices depends on the degree of structural complexity faced by each firm at different levels of its supply chain. In the same vein, Adhikary et al. (2020) link curvilinear effects of the supply chain complexity on environmental performance to different structural complexity dimensions.

An interesting aspect that emerges in this research area and that is still underrepresented in the literature, is the role that supply chain complexity can play in facilitating information sharing and processing between partners, so contributing to its environmental sustainability. As stated by Sharfman et al. (2009, p. 2): "*environmental issues in the supply chain context are uncertain, ambiguous, and equivocal*". Uncertainties can be associated with a lack of information about the environmental practices undertaken by the multiple actors involved in the supply chains with reference to products, materials and production processes (Busse *et al.*, 2017). One way to reduce these uncertainties is to increase the information flow across supply chain partners (Dahlmann and Roehrich, 2019; Sarkis, 2012). Dubey et al. (2020) consider that technological connectivity in the upstream supply chains effectively promotes information sharing and the visibility of partners, and that complexity capitalises these effects in sustainability performance. Gualandris et al. (2021) also find strong consistent results that supply chain density favours information sharing along the supply chain. Dense connections create a normative lock-in which ensures good environmental practices and outcomes. However, this literature does not adequately address the equivocality that complex supply chains may experience in processing information and, in particular, climate-change related information, which may not be resolved by using information technology. The management of equivocality is indicated as a growing priority to address sustainability in supply chains (Akhavan and Zvezdov, 2021; Dahlmann and Roehrich, 2019). For for this reason, we consider that the OIPT is the most appropriate theoretical lens to fill this gap.

3. Theoretical framework and hypotheses

3.1 OIPT and climate change in the supply chain context

The OIPT (Daft and Lengel, 1986; Galbraith, 1974) applied at inter-organisational level suggests that firms involved in supply chains carry out a variety of tasks whose effective accomplishment entails information-processing. In processing information, companies can incur uncertainty and equivocality (Daft and Lengel, 1986), and the way in which they cope with them will affect the result of the performed tasks.

Information uncertainty refers to the lack of the appropriate amount and quality of information required to perform a task (Galbraith, 1974). It is defined as "*the difference between the amount of information required to perform a task and the amount of information already possessed by the organisation*" (Daft and Lengel, 1986, p. 556). High information uncertainty reduces the predictability of the results of a task and companies can address it by collecting additional information (Galbraith, 1974) and sharing it at different levels of the supply chain (Akhavan and Zvezdov, 2021). On the other hand, equivocality is characterised by a state of vagueness, lack of precision and inexactness of information (Daft and Weick, 1984). When the collected information is chaotic, disorganised, confused, or ambiguous, organisations may experience equivocality because this information can lead them to multiple and potentially conflicting interpretations and understandings of a given problem during decision-making (March and Olsen, 1976). Indeed, unlike information uncertainty, equivocality is not a function of information quantity, but rather depends on information interpretation and absorption into companies' decision making (Dobrzykowski *et al.*, 2015). Equivocality, therefore, concerns potential distortions that can occur in the information interpretation process through which managers translate data into knowledge (Daft and Weick, 1984).

At the supply chain level, equivocality can be amplified because multiple firms with different objectives are involved in the interpretation process, and constrasting understandings may emerge, making the communication processes and the knowledge generation along the supply chain challenging, with potential negative effects on performance (Akhavan and Zvezdov, 2021; Eriksson *et al.*, 2016; Malhotra *et al.*, 2005). In a such context, the introduction of mechanisms enabling the management of equivocality can be necessary. Mechanisms that promote shared observations and discussions (Weick, 1979), or clarify data before these reach managers (Daft and Weick, 1984), can be crucial to achieve common interpretations along the supply chain, contributing to better performance (Dahlmann and Roehrich, 2019). According to Weick (1979), common interpretations can be facilitated by the introduction of conventional rules and/or shared interpretative schemes, because these help parts to shape what he refers to as ‘sense-making’ in relation to a given problem or phenomenon. Equivocality reduction thus requires to achieve a common information sense-making along the supply chain (Dahlmann and Roehrich, 2019), and mechanisms that activate this process can help firms to better acquire and assimilate information in complex supply chains (Malhotra *et al.*, 2005).

Climate change imposes additional challenges to supply chains (Dahlmann and Roehrich, 2019; Howard-Grenville *et al.*, 2014). It is defined as a pervasive phenomenon with no unique solution (Winn *et al.*, 2011), and as such, can bring important problems of equivocality (Akhavan and Zvezdov, 2021). Often, to tackle climate change, firms must make environmental decisions with limited and ambiguous information (Wu and Pagell, 2011). The transition to sustainable supply chains is made difficult because some environmental issues are not easily resolvable, especially within life-cycle oriented approaches where systemic changes are needed (Sharfman *et al.*, 2009). The multiple interactions between production processes and products of the different firms involved in the supply chain, as well as the multiple interactions between the operations across the supply chain and the ecological system provide an ambiguous map on how supply chain decisions affect the natural environment (Wu and Pagell, 2011). In other words, climate change stress equivocality and decision-makers should define an answer to reduce it (Akhavan and Zvezdov, 2021; Weick, 1979). A possible starting point is the introduction of mechanisms that favour sense-making around climate change issues because this can facilitate common interpretations, assumptions, and sense of the relevant issues, allowing organisations to operate on the same page (Daft and Weick, 1984; Weick, 1995).

Relying on OIPT and looking at the different dimensions of upstream supply chain complexity (i.e., horizontal, vertical, and spatial), we examine whether the different dimensions of structural supply chain complexity embed distinct capacities for effective information-processing and, hence, have different effects on GHG emissions at the firm and supply chain level. We also analyse whether managing the reduction of equivocality through written guidelines moderates these relationships.

3.2 Firm-level hypothesis development

At the firm level, research adopting OIPT emphasises that different organisational structures can entail different capacities for effective information-processing (Tushman and Nadler, 1978). Specifically, mechanic organisations, defined as rigid structures, perform better in a stable environment and are associated with lower levels of information-processing. At the other extreme, organic organisations, defined as boundaryless and flexible structures, tend to perform better in an unstable environment because they provide higher levels of information-processing (Tushman and Nadler, 1978). In the same vein, the literature on complex supply chain structures makes it clear that supply chain complexity is an outcome of firms' strategic decisions to cope with the uncertainties produced by unstable market dynamics (Chand *et al.*, 2022). This implies that, although the uncertainties fall outside the boundaries of the company's control, firms tackle them strategically by managing their supply chain structures. In these terms, supply chain complexity is a response to uncertainty and embeds different information-processing capabilities. As such, supply chain complexity should be beneficial for a firm's performance because it implies, initially, an internal absorption of complexity as part of the firm's overall strategy (Aitken *et al.*, 2016). Understanding whether this can occur for each dimension of structural supply chain complexity is an issue that has not yet been addressed in the literature.

3.2.1 Horizontal complexity and focal firms' GHG emissions reduction. Upstream horizontal complexity implies to increase the number of first-tier suppliers of a focal firm's supply network, and it is associated with direct or U-shaped effects on performance (e.g. Adhikary *et al.*, 2020; Lu and Shang, 2017; Sharma *et al.*, 2020). Specifically, in the sustainability context, horizontal complexity is viewed as beneficial for firms' environmental performance because the presence of multiple suppliers reduces companies' uncertainty. The focal firms can switch suppliers and this setting improves transparency and leads suppliers to adopt the environmental standards imposed by the focal firm. This approach suggests that the sustainability compliance of first-tier suppliers is the driver of focal firms' sustainability, but only until focal firms are able to monitor and control them (Adhikary *et al.*, 2020). The literature also shows that collaborations with suppliers implementing environmental practices affect the focal firms' innovation because these practices may require the adoption of new business models, processes and product features (Kähkönen *et al.*, 2017). In some industries, it is verified that first-tier suppliers adopt voluntarily sustainability practices and even implement operational practices in their sourcing to guarantee the accomplishment of sustainability parameters (Macchion *et al.*, 2020). Moreover, the design for reuse, recycling and disassembly requires focal firms to purchase from alternative sources of supply and make use of early supplier design involvement options (Carter *et al.*, 2000). Thus, the traditional logic of buyer pressure on first-tier suppliers through monitoring and control systems can be limitative in understanding the relationship between horizontal complexity and focal firms' performance.

Relying on the OIPT, we suggest that horizontal complexity can be a valuable source of information for focal firms (Bellamy *et al.*, 2014; Kim *et al.*, 2020). The high centrality that characterises first-tier suppliers (Gruchmann, 2022), can make them an important information source which focal firms can access as horizontal complexity increases. To achieve sustainability goals, indeed, the needs of focal firms may lie outside their traditional frame of competencies, requiring the collection of a lot of information from first-tier suppliers to better understand environmental problems. In these terms, first-tier suppliers can help focal firms to activate transformation processes enabling the reduction of focal firm's GHG emissions.

According to the classic theory of horizontal complexity, the establishment of a direct tie can be assimilated to the creation of a ‘bit’ of information (Commons, 2008). When companies increase the upstream horizontal complexity to cope with uncertainty, they substantially produce an accumulation of ‘bits’ of information related to specific areas of expertise. This concentration of bits of information coming from several sources of information in a same area of specialization can contribute to achieve a sort of validation and consistency of the collected information, leading firms to make the correct decision. In short, through horizontal complexity, focal firms would look for information redundancy to form impressions about a problem (Alves and Mata, 2019).

Processing a lot of information in a same specialisation area allows them to focus on "what it is best to do" to perform a task (Commons, 2008). In these terms, horizontal complexity entails information-processing capabilities, because increasing contacts with first-tier suppliers should help focal firms to achieve sense-making about environmental problems, leading them to progressively find the most appropriate solutions to reduce GHG emissions.

H1a. Upstream horizontal complexity decreases focal firms' GHG emissions.

3.2.2 Vertical complexity and focal firms' GHG emissions reduction. Upstream vertical complexity refers to the hierarchical level or depth of the focal firm's supply network and count with contrasting views on what its effects on focal firms' performance are. Some researchers suggest that there is a linear and positive relationship between vertical complexity and firm performance, due to the multiple operational benefits, in terms of great economies of scale, access to new technologies and deep expertise that derive from increasing links with lower-tier suppliers (Kim *et al.*, 2020). In contrast, other studies argue a U-shaped relationship, suggesting that vertical complexity offers the opportunity to access varied information and expertise that allows novel knowledge combination as well as knowledge transfer across sectors, improving firms' performance (e.g. Flynn *et al.*, 2010). However, these positive effects can be appreciated only up to a certain threshold, because thereafter a focal firm is no longer able to handle large and diverse information (Adhikary *et al.*, 2020; Sharma *et al.*, 2020).

Applying the OIPT, we argue that vertical complexity entails information-processing capabilities that can contribute to reducing focal firms' GHG emissions but only up a point. Lower-tier suppliers can provide access to unique market information and other resources, giving the focal firm a wider picture of technological dynamics and competition across diverse markets. As vertical complexity increases, the information that comes from suppliers in varied sectors increases. The more such information can be harnessed from lower-tier suppliers in a vertically complex supply base, the greater the opportunity to improve performance (Sharma *et al.*, 2022a). However, the focal firm in vertically complex supply chains needs to manage and arrange the information at different supply chain levels. Commons (2008) suggests that performing a task under vertical complexity requires information to be organised hierarchically, in the form of tasks and subtasks, implying greater information-processing efforts. Besides, in vertical complexity the suppliers' specialisation can be wide (Lu and Shang, 2017). Hence, firms dealing with extended information coming from several types of suppliers, whose levels of specialisation and expertise may be highly diversified and distant from their knowledge, above a certain threshold, can incur equivocality. This can hinder the achievement of sense-making about environmental issues and so the possibility to reduce GHG emissions. Beyond a certain point, therefore, in vertically complex supply chains, focal firms can experience severe difficulties in information-processing that can inhibit the possibility of assimilating information in such a way as to convert it into the knowledge needed to reduce GHG emissions.

> *H1b.* There is a U-shaped relationship between upstream vertical complexity and focal firms' GHG emissions.

3.2.3 Spatial complexity and focal firms' GHG emissions reduction. Spatial complexity is associated with the geographical dispersion of a focal firm's supply base. Most studies posit negative and linear relationships between spatial complexity and firm performance. This is because firms with worldwide suppliers endure longer travel distances and variable lead times, increasing their vulnerability in terms of disruptions (Bode and Wagner, 2015; Brandon-Jones *et al.*, 2015). They have also to devote significant time, effort and resources to this type of suppliers and deal with increasing ambiguities in information and material flows that destabilise firm innovation (Sharma *et al.*, 2020), and impaire carbon performance (Adhikary *et al.*, 2020).

Under OIPT, spatial complexity offers the focal firm opportunities to access information from multiple countries. This provides the firm with unique possibilities to recombine resources and knowledge, expanding its opportunities to improve performance (Leiponen and Helfat, 2010). However, spatial complexity stresses the problem of ambiguities in the collected information mainly because cultural differences may exist between focal firms and suppliers in addressing environmental issues. Increasing numbers of relationships with dispersed suppliers can involve managing partners with different cultural backgrounds and requires the adoption of different approaches to the relationships to tackle environmental problems. Understanding suppliers' customs and dealing with differences across countries can be a source of frustration and require high information-processing capacities to decrease any potential negative effect on the focal firm's performance (Brandon-Jones *et al.*, 2015; Choi and Krause, 2006). Challenging information processing could also hinder shaping relational capital with suppliers, which is needed to implement sustainability practices (Chowdhury *et al.*, 2023). Like vertical complexity, therefore, we suggest that when spatial complexity increases, managing very varied information could lead companies to absorb and correctly process it up to a certain point. Beyond that point, they can incur equivocality. Cultural differences can be the source of contrasting interpretations and diverse understandings of environmental problems, not helping focal firms to achieve sense-making in their information-processing and, consequently, preventing advances in reducing their GHG emissions.

H1c. There is U-shaped relationship between upstream spatial complexity and focal firms' GHG emissions.

3.3 Supply chain-level hypothesis development

Analysis of the effects of complexity on GHG emissions at the supply chain level, where GHG direct emissions from focal firms and indirect GHG emissions from their supply chain partners are considered as a whole, requires a change to the paradigm. The traditional approach that sustainable supply chain performance can be governed by the focal firm through monitoring and control systems is unsustainable in changing markets, and even difficult to implement when the goal is to improve performance beyond the focal firms' boundaries. In this vein, CAS theory (Choi *et al.*, 2001) suggests that managers can experience frustration and helplessness in predicting changes in their tertiary supplier level, which are naturally outside their control, as well as in mapping every change in their relationships with their suppliers. Managers need to understand the supply chain behaviour in a more complete manner and develop mechanisms that are more likely to be effective in dynamic environments (Choi *et al.*, 2001). This approach leads to considering the supply chain as an inter-organisational system, where the structuring of processes or the same configuration of the system creates interdependence between partners, contributing to the absorption of knowledge, operational efficiency, and access to increasing information-processing capabilities in the supply chain (Malhotra *et al.*, 2005). This study analyses the information-processing that can be embedded in the different dimensions of the structural supply chain complexity with the aim of understanding how these can affect the GHG emissions of the entire supply chain.

3.3.1 Horizontal complexity and supply chain GHG emissions reduction. At the firm level, we suggested that horizontal complexity may positively affect GHG emissions reduction. We argued that this complexity dimension provides focal firms with access to increased information for each area of knowledge, allowing them to achieve the information consistency needed to reduce equivocality and absorb information in such a way as to make the right decisions to abate GHG emissions in their operations. At the supply chain level, on the other hand, the effects of horizontal complexity on the GHG emissions of the entire supply chain may actually be outside the direct control of the focal firms and will depend on how the information is shared and processed along the supply chain.

Information sharing in supply chains has always been considered a major issue for achieving operational efficiency (Lee *et al.*, 1997), and the contemporary research on multi-tier supply chain structures particularly stresses its importance for attaining sustainable performance (Dahlmann and Roehrich, 2019; Wong *et al.*, 2015). This literature provides important insights into this topic since increasing horizontal complexity implies increasing information mediation of the first-tier suppliers in the relationship between the focal firms and the lower-tier suppliers. Multi-tier literature recognises that the first-tier suppliers have a key role in disseminating information on sustainable standards upstream in the supply chain (Grimm *et al.*, 2014), where potential violations and lack of transparency can frequently occur (Villena and Gioia, 2020). In this role, first-tier suppliers can help to reduce uncertainty and increase transparency along the supply chain, potentially improving the sustainability throughout the entire supply chain. First-tier suppliers are seen as double agents: as primary agents, they are responsible for making critical decisions, such as selecting and deselecting sub-suppliers according to the focal firms' sustainability requirements; as secondary agents, they can help to disseminate information on sustainability standards to their suppliers' operations (Wilhelm *et al.*, 2016). In these roles, they also work as assimilators of knowledge, thereby providing assistance to lower-tier suppliers (Jia *et al.*, 2021).

The literature confirms the importance of increasing relationships with first-tier suppliers, which have been positively associated with collective innovation (Carnovale and Yeniyurt, 2015) and environmental transparency (Gualandris *et al.*, 2021). The good-will of the first-tier suppliers in promoting boundary-spanning actions has been linked to specific characteristics of the first-tier suppliers and even to the network context in which they are embedded (Jia *et al.*, 2021; Wilhelm and Villena, 2021). Researchers find that the growth of links with first-tier suppliers can promote mimetic behaviours among them, leading to capitalising the effects of collaborations on environmental performance (De Stefano and Montes-Sancho, 2018). Also, complex supply bases enable trust, which in turn facilitates information sharing regarding climate change between supply chain members (Dahlmann and Roehrich, 2019). Hence, we suggest that horizontal complexity can be a suitable structure to promote cascading effects because it can activate contagious behaviours among first-tier suppliers.

Horizontal complexity can work as a bridge across which information flow can be facilitated upstream in the supply chain (Defee and Stank, 2005). When horizontal complexity increases, the width of the bridges expands across the network, potentially activating positive, complex and contagious effects (Centola and Macy, 2007) between first-tier suppliers, leading them to spread information about sustainable practices in the upstream supply chain.

In this process, however, it is important to consider the way in which the first-tier suppliers interpret information (Jia *et al.,* 2021). Similar to what happens at firm level, we suggest that in the presence of high horizontal complexity, the information will be processed by several suppliers with similar levels of expertise. Dialogue and conversations among first-tier suppliers with similar expertise, and the focal firms could work as fast information validation (Richter *et al.,* 2009), reducing potential equivocality in information-processing. Hence, we state that horizontal complexity can facilitate sense-making about environmental problems and diffuse valuable information upstream helping to take actions that enable the reduction of the GHG emissions of the entire supply chain. However, it is also possible that at the supply chain level, partners are not able to adequately discount the redundant information generated by the width of the bridges, with the risk that potential interpretative bias may emerge (Alves and Mata, 2019). For this reason, we also suggest that after a certain point increasing horizontal complexity companies can incur equivocality that could be detrimental to achieving lower GHG emissions of the entire supply chain.

H2a. There is a U-shaped relationship between upstream horizontal complexity and the GHG emissions of the entire supply chain.

3.3.2 Vertical and spatial complexity and supply chain GHG emissions reduction. At the firm level, we argued that in presence of vertical and spatial complexity, focal firms are hierarchically and culturally distant from their suppliers, and this can generate equivocality in information-processing, limiting, after a certain point, its absorption into the focal firms' operations with non-linear effects on GHG emissions reduction. At the supply chain level, the equivocality caused by vertical and spatial complexity may be amplified because information-processing involves several parties with different expertise and cultural backgrounds; in this context, higher levels of inter-organisational information-processing are required to convert information into the knowledge needed to achieve sustainable supply chain performance (Blome *et al.*, 2014; Dahlmann and Roehrich, 2019). Moreover, with regard to the possibility that vertical and spatial complexity can contribute to disseminating sustainable-related information along the supply chain, it can be observed that when there is distance between partners, the relationships present structural weakness, and this inhibits the ability of one party to influence the others. Centola and Macy (2007), define these relationships non-transitive suggesting that the diffusion of information requires redundant ties because the information needs to be confirmed and reinforced from multiple sources. In contrast, distant ties can be beneficial to spread new information, but their uniqueness becomes a weakness in promoting contagious behaviour among suppliers (Centola and Macy, 2007).

In vertical complexity, direct contacts between focal firms and lower-tier suppliers are described as scarce and can occur when first-tier suppliers do not take responsibility for communicating sustainability requirements to sub-suppliers (Mena *et al.*, 2013). The direct contacts with lower-tier suppliers, however, can produce ill-structured flows of information. They cannot be mediated by the first-tier suppliers and can be based on the specific assessment that the focal firms have to do for each sub-supplier (Grimm *et al.*, 2016). Vertical complexity, therefore, implies that several organisations have to process diverse and specific information at each level of the supply chain. Language differences and unstructured communication channels among supply chain partners may foster the emergence of equivocality, affecting the result of the information-processing and requiring mechanisms to coordinate and control information between organisational boundaries (Akhavan and Zvezdov, 2021; Pederneiras *et al.*, 2022). In other words, vertically complex supply chains could not embed high information-processing capabilities to achieve sense-making about environmental issues, implying only increasing GHG emissions at the supply chain level.

H2b. Upstream vertical complexity increases the GHG emissions of the entire supply chain.

In the same vein, increased spatial complexity is associated with highly unpredictable supplier behaviours (Brandon-Jones *et al.*, 2015). The literature shows that the geographical distance can facilitate carbon emission information being hidden (Adhikary *et al.*, 2020). This type of behaviour inevitably affects the flow of information along the supply chain and limits its processing. Villena and Gioia (2018) highlight an essentially passive attitude of suppliers towards sustainability issues, especially when they operate in countries where environmental regulations are less demanding. Moreover, global sourcing, compared to national sourcing, is associated with a lack of transparency (Wagner and Bode, 2006) and fewer collective disclosures (Gualandris *et al.*, 2021). This is due to differences in interests and goals and the poor transferability of practices that are developed to conform to particular operational settings and local institutions. The different cultures of the countries where the suppliers operate can, indeed, play an important role in shaping suppliers' orientations and values about climate change (Pederneiras *et al.*, 2022), affecting the adoption of certain practices. These differences can hinder the achievement of a shared sense-making between suppliers and, thus, the implementation of consequent actions to reduce total GHG emissions. All these aspects imply that spatial complexity results in severe information uncertainties and equivocality that can negatively affect the achievement of lower GHG emissions at the supply chain level.

H2c. Upstream spatial complexity increases the GHG emissions of the entire supply chain.

3.4 The moderating effects of reducing equivocality through written guidelines

As argued above, especially in vertical and spatial supply chain complexity dimensions, equivocality can be an issue, hampering the reduction of GHG emissions at the firm and supply chain level. Equivocality emerges due to a failure to define problems clearly that creates confusion, making it more difficult to make decisions. It refers to conditions that evoke multiple meanings, which cannot be easily merged or compromised. Organisations are called upon to manage equivocality by imposing meanings on events; meanings that can reduce, maintain, or increase equivocality (Putnam and Sorenson, 1982). Equivocality is therefore related to interpretation in information-processing, i.e., to “the process of translating events and developing shared understanding and conceptual schemes among members of upper management” (Daft and Weick, 1984, p. 286). In Weick's (1979) model, choosing meanings involves defining who should handle interpretations, the rules for processing interpretations, and the activation of communication cycles to act upon interpretations. Brun and Saestre (2008) describe the process of equivocality by showing that it occurs when a single cue is associated with several interpretations. If, for example, the cue is the development of a new product that involves several actors, equivocality happens when the parts may develop different understandings and, consequently, propose diverse responses or actions. Hence, reducing equivocality requires actors to share the same bases, which will help them to shape a common sense-making and develop convergent interpretations.

In complex supply chain structures, partners can be asked to interpret the cue of how to reduce their GHG emissions in a way that positively affects the other partners' GHG emissions, thereby contributing to the reduction of GHG emissions of the entire supply chain. Effective mitigation strategies at the supply chain level require organisations to know the environmental impact of their own processes and operations, as well as how their actions affect the environmental impact of their partners' processes and operations (Sarkis, 2012). Since climate change is a complex and wicked problem, it is not an easy cue to interpret, and the partners in complex supply chain structures could develop different understandings and deliver distinct ideas or actions on how to achieve better environmental supply chain performance. In this way, different understandings can hinder the possibility of decreasing GHG emissions especially at the supply chain level. One solution is to reduce equivocality at the source, that is, by introducing shared schema to prevent multiple interpretations of the cue with the consequence of generating different actions that negatively affect performance.

The introduction of mechanisms to reduce equivocality at the source can be beneficial for focal firms, particularly in the cases of vertical and spatial complexity where backgrounds and cultural differences can be a barrier to properly performing the information-processing. Research reveals that in complex operating systems, the adoption of shared schema, such as standard operating procedures, written procedures and rules, can help to overcome barriers, decreasing the negative effects of complexity on environmental performance (Wiengarten *et al.*, 2017). The introduction of shared schema can standardise operating procedures and create routines in the information production, diffusion and storage, reducing potential distortions of the focal firms' information-processing. This would facilitate the correct absorption of information into the firm's operations with positive moderation effects on the GHG emissions reduction.

> *H3a*. The introduction of written guidelines as shared schema to reduce equivocality moderates the relationship between upstream complexity and focal firms' GHG emissions, with greater effects on vertical and spatial complexity than horizontal complexity.

At the supply chain level, mechanisms such as shared written documents, target planning, and data analyses among others, are also identified as useful to reduce uncertainty and/or equivocality along supply chains (Akhavan and Zvezdov, 2021). Particularly in complex settings, operating principles or technical standards guide managers' decisions related to improving environmental performance because they create a common culture and work norms that make the reactions of managers to uncertain and complex events more predictable and easier to coordinate (Choi and Krause, 2006; Wiengarten *et al.*, 2017; Wu and Pagell, 2011). Also, by publishing common guidelines, focal firms can clarify some concepts, their particular features and even establish the methodology to be followed by suppliers in collecting data. Indeed, formal communication mechanisms, such as written guidelines, would send an unequivocal message along the supply chain, making it possible to better achieve a common interpretation of a given issue throughout the supply chain and, consequently, improved environmental performance. Furthermore, the written documents can provide the core elements needed to undertake the tasks, which will also make their processing simpler for supply chain partners, especially when they have different backgrounds and cultures. Hence, we propose that if the focal firms introduce written guidelines into their supply chains, these can contribute to equivocality reduction, decreasing the negative effects of complexity on GHG emissions at the supply chain level, especially in the case of vertical and spatial structural complexity.

> *H3b*. The introduction of written guidelines as shared schema to reduce equivocality moderates the relationship between upstream complexity and supply chain GHG emissions, with greater effects on vertical and spatial complexity than horizontal complexity.

A conceptual model summarising the proposed hypotheses is shown in Figure 1.

Figure 1. ABOVE HERE

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4. Method

4.1 Data collection and sample

We tested hypotheses using a dataset constructed from three secondary sources widely used in the literature (e.g. Adhikary *et al.*, 2020; Busch *et al.*, 2022; Sharma *et al.*, 2020): Bloomberg, Trucost and Compustat. Bloomberg is the main source employed to measure complexity since it provides detailed corporate and contractual ties information through the "Supply Chain Function" (Bloomberg SPLC). Covering U.S. and non-U.S. suppliers, Bloomberg SPLC gathers data from several sources such as news articles, trade publications, firm websites, and private communications. Trucost is a leading provider of environmental data with coverage of over 15,000 companies, representing 95% of global market capitalisation. It encompasses GHG emissions data from Carbon Disclosure Project (CDP) and other sources, including those published in the corporate report, and it is the most reliable and comprehensive source of GHG emissions data. Finally, Compustat, which is largely used in our field, provides financial information for publicly traded firms.

Our initial sample contained all constituent firms of the SP500 index. From this list, we excluded financial and real estate firms, obtaining a sample of 401 companies with a study period of 2016-2018. Among these 401 firms, we removed those companies that did not have available information in Bloomberg or Trucost. This resulted in an unbalanced panel data of 394 firms with 1,172 firm-year observations, as some firms had missing values for some control variables. Table I shows the number of SP500 firms retained in the data construction process after each merger step, which covers approximately 80% of the total SP500 constituents.

Table I. ABOVE HERE

4.2 Measures

The variables employed in the empirical analysis are presented in Table II.

Table II. ABOVE HERE

4.2.1 Dependent variables. To assess the GHG emissions at the firm and supply chain level, we used the emissions data from Trucost. Specifically, we employed the

Scopes 1, 2 and 3 as defined by the GHG Protocol, using Scope 1 for the firm's GHG emissions, and the sum of Scopes 1, 2, and 3 for the GHG emissions of the entire supply chain. The GHG Protocol classifies Scope 1 emissions as direct GHG emissions because released by the industrial processes of facilities owned or directly controlled by the company. The GHG protocol also defines Scopes 2 and 3 emissions as indirect because they are derived from sources not directly controlled by the company. Scope 2 emissions are associated with GHG emissions from the generation of purchased energy, whereas Scope 3 emissions are all those indirect emissions, not included in Scope 2, that occur upstream and downstream in the supply chain. Following the logic of the life cycle assessment, taken together, direct and indirect emissions represent the emissions of the entire supply chain.

In line with King and Lenox (2000), we computed standardised measures. At firm level, we estimated a production function between size for each four-digit code of Global Industry Classification Standard (GICS) within each year using OLS regression, considering the entire universe of firms included in Trucost. Hence, the relative GHG emission performance of each firm was obtained from the standardised residual between the observed and predicted GHG emissions given its size and sector. We estimated the relative GHG emissions at supply chain level in the same way. Therefore, we employed the relative carbon emission performance at firm and supply chain level as dependent variables in our empirical analysis.

4.2.2 Independent variables. This study included the core dimensions of upstream supply chain complexity (i.e., horizontal, vertical, and spatial), their corresponding quadratic terms, and the reduction of equivocality through written guidelines. In line with previous studies (see Table II for details) that have analysed supply chain complexity, we operationalised it as follows. Horizontal complexity was measured as the total number of first-tier suppliers of the focal firm. Vertical complexity was measured as the average number of second-tier suppliers per first-tier supplier. Spatial complexity was measured as the total number of countries of the first-tier supplier based on their headquarters.

We approach the reduction of equivocality through the introduction of written guidelines because, according to Weick's (1979) model, in the process of choosing the meaning of information, the presence of some criteria or guidelines can act as causal maps of the information interpretation (Putnam and Sorenson, 1982). This variable was first approximated through the Bloomberg data that indicates whether the focal firm has publicly disclosed the suppliers' guidelines for environmental, social and governance (ESG) areas. For those firms that Bloomberg identified as having suppliers' ESG guidelines, we reviewed these guidelines, looking for the presence of rules or procedures that explicitly referred to climate change issues. We assigned the variable equivocality a value of 0 if the focal firm had suppliers' guidelines that have not passed the climate change validation process discussed above, and 1 otherwise, implying this latter equivocality reduction.

4.2.3 Control variables. We considered control variables at the focal firm (buyer) and relationship level. At buyer level, we employed the following variables: number of customer firms, number of products, advanced climate capabilities, carbon disclosure, size, profitability, production efficiency, age, market share, R&D intensity, and superior IT. The number of customer firms, which also captured the downstream detail complexity, was included as the total number of customer firms that the focal company had in each year. Similarly, the number of products, which was considered as an element of the internal manufacturing complexity, was estimated using the classification of the family product as the total number of different family products provided by the focal firm. The advanced climate capabilities variable was captured through the buyer's products. It took the value 1 if the company had developed and/or launched products that addressed the future impact of climate change and/or mitigated the contribution of its customers to climate change during this year or in the previous two years, being 0 otherwise. Carbon disclosure was measured through the percentage of GHG emissions disclosure reported by the focal firm in each year. Size was operationalised as logged assets. Profitability was reflected through return on assets. Production efficiency was calculated as a relative measurement of the focal firm's production efficiency with respect to its industry at four-digit NAICS level. Age captured the company's maturity in business, being the number of years since its foundation. Market share was computed as the percentage of the firm's sales over the total industry sales at four-digit NAICS level. R&D intensity was calculated as the ratio of R&D expenses to total sales. Superior IT captured the presence of advanced information systems processing in the company. It took the value 1 if the focal firm is listed in the special issue of Elite 100 provided by InformationWeek, a leading IT publication in the United States, and 0 otherwise.

At relationship level, we employed supplier and customer dependency. Supplier dependency was operationalised as the ratio of supplier's sales to the focal firm over total supplier sales. Customer dependency was the customer's proportion of cost of goods provided by the focal company.

4.3 Model specification

Hypotheses were tested by specifying random effects regression with robust standard errors. The Breusch and Pagan Lagrange multiplier test and the Hausman test confirmed that this was the correct specification. We also ran the homoscedasticity test with the result that the null hypothesis was rejected, meaning that the option of robust standard errors should be introduced to control for the presence of significant heteroscedasticity in our sample.

The full testing models at the firm and supply chain level are specified as follow:

$$\textit{Firm's GHG emissions}_{i,t} = \beta_1\ \textit{horizontal complexity}_{i,t-1} + \beta_2\ \textit{vertical complexity}_{i,t-1} + \beta_3\ \textit{spatial complexity}_{i,t-1} + \beta_4\ \textit{vertical complexity}^2_{i,t-1} + \beta_5\ \textit{spatial complexity}^2_{i,t-1} + \beta_6\ \textit{equivocality}_{i,t-1} + \beta_7\ \textit{horizontal complexity}_{i,t-1} \times \textit{equivocality}_{i,t-1} + \beta_8\ \textit{vertical complexity}_{i,t-1} \times \textit{equivocality}_{i,t-1} + \beta_9\ \textit{spatial complexity}_{i,t-1} \times \textit{equivocality}_{i,t-1} + \textit{Controls}_{i,t-1} + \varepsilon_{i,t-1}$$

$$\textit{Supply chain GHG emissions}_{i,t} = \beta_1\ \textit{horizontal complexity}_{i,t-1} + \beta_2\ \textit{vertical complexity}_{i,t-1} + \beta_3\ \textit{spatial complexity}_{i,t-1} + \beta_4\ \textit{horizontal complexity}^2_{i,t-1} + \beta_5\ \textit{equivocality}_{i,t-1} + \beta_6\ \textit{horizontal complexity}_{i,t-1} \times \textit{equivocality}_{i,t-1} + \beta_7\ \textit{vertical complexity}_{i,t-1} \times \textit{equivocality}_{i,t-1} + \beta_8\ \textit{spatial complexity}_{i,t-1} \times \textit{equivocality}_{i,t-1} + \textit{Controls}_{i,t-1} + \varepsilon_{i,t-1}$$

where controls included the set of control variables mentioned above, and the industry and year dummy variables. The independent and control variables are lagged one year with respect to the dependent variables.

4.3.1 Endogeneity. The complexity regressors are potentially endogenous as the design of a network is a strategic choice of the focal firm, being widely discussed in the literature (Borgatti and Halgin, 2011). Focal firms mainly determine their network configuration, with the decision regarding who will be their direct suppliers driving the following tier-n suppliers and, thereby, the upstream supply chain complexity. Since this is a strategic decision where the focal firm decides whom will be part of its network, the complexity dimensions can be endogenous.

Endogeneity can occur for two main reasons. First, it may be due to omitted variables. The extensive set of control variables included in the analysis can significantly mitigate this concern as well as the usage of random effects models. Second, it may be due to simultaneity. This means that the complexity dimensions and GHG emissions are determined simultaneously. While the complexity variables are included with a one-year lag to avoid reverse causality, further empirical implementation is needed. Among the estimators to address endogeneity, we employed the control function approach (Wooldridge, 2015), as we had non-linear terms for the upstream complexity dimensions. Grounded on theory, we considered the three main elements that can shape the firm's supply chain complexity. These were upstream complexity of its peers (i.e., mimetic behaviour), the firm's reputation (i.e., to easily attract more firms to its network), and operating in an uncertainty environment (i.e., having alternative ties to easily make the adjustments). In each control function, we included all the control variables considered in the interest model plus other variables that measured the corresponding complexity dimension of the focal firm peers, whether the focal firm was in the list of Fortune World's most admired companies and whether it was traded on the NASDAQ stock market. The reduced form residuals obtained from the control function regressions were then added as control variables in the GHG emissions regressions to correct for the endogeneity. By using the control function approach, we overcame the limitation of identifying two instruments (i.e., one for the linear and another for the quadratic term) for each upstream complexity dimension, with our estimates being more efficient than those provided by instrumental variables technique (Wooldridge, 2015).

5. Results

In the Supplementary material (Table A1), we provide the descriptive statistics and the correlation of the variables used in the analysis.

5.1 Results of the upstream complexity dimension on GHG emissions

Tables III and IV display the results for the GHG emissions performance at the focal firm and supply chain level respectively using the control function approach to correct for endogeneity. In both cases, the coefficients of the complexity residuals as additional regressors in the second stage are significant, supporting the need to apply the control function approach to obtain unbiased results.

Table III. ABOVE HERE

In Table III, Model 1 provides the results of the linear effects of the complexity dimensions on the focal firm's GHG emissions. Models 2 and 3 show, respectively, the results when we introduce the proposed quadratic and moderating effects into the analysis. Regarding the complexity dimensions, we find that horizontal and spatial complexity and the quadratic term of vertical complexity are all significant. Consistent with H1a, the results support that as upstream horizontal complexity increases, the focal firm's GHG emissions decrease (Model 1: $\beta = -0.0251$, $p < 0.01$). In the case of vertical and spatial complexity, in which we hypothesise the presence of non-linear effects, we only find significance for vertical complexity. Therefore, H1c is not supported. Regarding the vertical complexity, although its quadratic term is significant (Model 2: $\beta = 0.002$, $p < 0.05$), it does not satisfy the three-step procedure to validate the existence of significant quadratic effects suggested by Lind and Mehlum (2010). This implies that the effect of upstream vertical complexity on the focal firm's GHG emissions becomes partially exponential after reaching a threshold. Thus, H1b is not supported.

In Model 3, we introduce the interactions for vertical and spatial dimensions to examine the moderating effects of equivocality on the focal firm's GHG emission. The results show that its reduction only significantly moderates the relationship between upstream vertical complexity and focal firm's GHG emissions (Model 3: $\beta = -0.0099$, $p < 0.10$). Therefore, we find support for H3a only in the case of vertical complexity.

With respect to the controls, the variables number of customer firms, carbon disclosure, advanced climate capabilities, focal firm size and its profitability, market share, R&D intensity and customer dependency have negative and significant effects on the focal firm's GHG emissions. In contrast, the number of products and production efficiency have positive and significant effects on GHG emissions at the firm level.

Table IV. ABOVE HERE

Models 1 and 2 in Table IV show the results of the proposed linear and quadratic effects of upstream complexity dimensions on the GHG emissions at the supply chain level, respectively. The upstream horizontal complexity and its quadratic term are both negative but not significant. Hence, H2a is not supported. The upstream vertical complexity is positive and significant (Models 1 $\beta = 0.4743$, $p < 0.05$; Model 2 $\beta = 0.4734$, $p < 0.05$), as suggested by H2b. Consistent with H2c, as the upstream spatial complexity increases (Model 1 $\beta = 1.3693$, $p < 0.05$; Model 2 $\beta = 1.3546$, $p < 0.05$), the

GHG emissions of the entire supply chain also increase. Similar to the focal firm level, the reduction of equivocality in the case of upstream vertical complexity decreases the GHG emissions of the entire supply chain (Model 3 $\beta = -0.0199$, $p < 0.05$). Therefore, the empirical evidence related to moderating effects only supports H3b in the case of vertical complexity.

Regarding the control variables, along with the significant effects, it is notable that the variable superior IT is a negative significant predictor of the GHG emissions at the supply chain level. This finding is discussed in more detail in the discussion.

5.2 Control function approach results

Table V shows the results of the control function regression on the upstream complexity dimensions. The complexity dimensions of peer companies are all significant (Horizontal $\beta = 0.7236$ $p < 0.01$; Vertical $\beta =1.2201$ $p < 0.01$; Spatial $\beta = 0.4658$ $p < 0.01$). In the case of firm reputation measured through the Fortune list, it predicts positively the dimension of spatial complexity, but negatively that of vertical complexity. The uncertainty environment as measured through trading on the NASDAQ stock market does not appear to significantly influence any of the dimensions of the upstream structural complexity.

Table V. ABOVE HERE

5.3 Robustness test

We conducted additional robustness tests and used alternative variables to operationalise GHG emissions, obtaining results that support all of our main findings. We also performed the analysis using only indirect emissions (i.e., Scopes 2 and 3) as the dependent variable, with the results being in the supplementary material. As recent studies (e.g. Busch *et al.*, 2022) have pointed out that the existence of significant differences in the results may depend on the source of GHG emissions data, we additionally tested our hypothesis using CDP data. In this case, we only included SP500 firms that report their GHG emissions to this programme, with the coverage of SP500 constituents being reduced to 50%. As shown in the supplementary material (Tables A3 and A4), there are some differences. In particular, the horizontal complexity becomes significant in the model of supply chain GHG emissions, but the quadratic term remains insignificant, in line with our findings. Also, the variable equivocality becomes a significant predictor in the total indirect emissions (i.e., Scopes 2 and 3). This may be due to the fact that focal firms participating in CDP also invite their suppliers to submit their GHG emissions data, thereby introducing common procedures. Therefore, our results using Trucost as a main source are more conservative, having better coverage of the target population (i.e., almost 80% vs 50%). Given this difference and in line with Culot et al. (2023) recommendations, it becomes critical to add a specific control variable into the analysis that accounts for it, as we have done in our analysis through the variable carbon disclosure.

6. Discussion

6.1 Discussion of results

The concept of "less is more" is not easily applicable to the supply chain. As companies look to reduce costs, increase revenues or mitigate supply risks, they inevitably also increase complexity. The analysis of complexity in the supply chain structure has become a topic of growing interest, especially to understand whether it is compatible with the achievement of sustainability goals (Adhikary *et al.*, 2020; Gualandris *et al.*, 2021). However, the research seems to remain rooted in its conventional paradigms, preventing this field from evolving adequately (Akhavan and Zvezdov, 2021; Dahlmann and Roehrich, 2019; Pederneiras *et al.*, 2022). There is a strong focus on firm level analysis either in terms of performance or governance approach, according to which the sustainability of supply chains is dependent on the capacity of the focal firms to directly control suppliers. The current need to reduce indirect GHG emissions, above all, highlights the limits of these approaches, requiring analyses that go beyond the focal firm perspective (Macchion *et al.*, 2020) to reconcile potential trade-offs between firm and supply chain sustainability goals. Supply chain complexities viewed solely from a company perspective can have drawbacks at the supply chain level. Therefore, they need to be considered from a more holistic perspective. For this reason, relying on OIPT, this study proposes assessing how the supply chain complexity, analysed in its multiple dimensions, entails certain information-processing capabilities, affecting the achievement of lower GHG emissions at the focal firm and supply chain level.

6.1.1 Firm-level results. In contrast with the curvilinear result obtained by Adhikary et al. (2020), our findings confirm that horizontal complexity can be beneficial at the firm level because it contributes at any given point to reduce focal firms' GHG emissions. Increasing contacts with first-tier suppliers can be a valuable and consistent source of information that can help focal firms to rethink and improve their operations. This result is consistent with the strategic perspective of supply chain complexity (Aitken *et al.*, 2016) and with the unexpected finding that shows the positive impact of horizontal complexity on operational purchasing performance when firms are a highly strategic purchaser (Ateş and Memiş, 2021). Furtherly, vertical and spatial complexity result to be dysfunctional for focal firms' GHG emissions. We do not find a U-shaped relationship between vertical complexity and focal firms' GHG emissions. This result contrasts with previous studies (Adhikary *et al.*, 2020) and could be associated with the limited adherence of lower-tier suppliers to the sustainability requirements of focal firms (Macchion *et al.*, 2020; Villena and Gioia, 2020), with the consequent ineffectiveness of transmitted information, at least from a sustainability point of view. Moreover, serious difficulties in information-processing can characterise this complexity dimension, as focal firms have to process information coming from several suppliers with different levels of specialisation, sometimes without counting on the intermediary role of the first-tier suppliers. Thus, they may manage high levels of equivocality. Recent studies show that for sustainability goals, supply chain intermediaries can add value to the buyer-supplier exchange by facilitating sustainability-related information transfer (Cole and Aitken, 2020). The results for spatial complexity, on the other hand, are consistent with those suggested by previous research indicating that spatial complexity has linear and negative effects on focal firms' GHG emissions.

The introduction of written guidelines as a mechanism to reduce equivocality seems to play a key moderating role in achieving lower focal firms' GHG emissions in highly vertically complex supply chain structures. This result seems to support the arguments of Jensen and Szulanski (2007), who suggest that the introduction of schema can help to establish organisational routines and allow the examination of elements that may not be publicly available outside the company, as well as to increase the likelihood that aspects of the routine that are tacit or causally ambiguous are transferred outside firms. In these terms, it is possible that the adoption of written guidelines in vertically complex supply chains can help focal firms to establish routines along supply chain to process information and, over time, facilitate equivocality reduction and information absorption with the effect of decreasing the negative impact of vertical complexity on the firm's GHG emissions.

6.1.2 Supply chain-level results. In contrast to the firm level, increasing horizontal complexity does not have a significant effect on reducing GHG emissions of the entire supply chain. This result seems to be partially consistent with Common (2008)'s framework, which shows that in the presence of horizontal complexity, the advantage of information consistency to understand problems can be countered by the need to organise information that is cumulatively redundant. It is possible that at the supply chain level, companies are not able to discount information redundancy, and may need sophisticated shared software and computing methods to do so (Diniz *et al.*, 2021; Sharma *et al.*, 2022b). These would enable better tracking of information in a way that could be useful to achieve the consistency needed to promote contagious behaviour among first-tier suppliers and significantly reduce GHG emissions. A surprising result is that the introduction of written guidelines to reduce equivocality has no significant effect on horizontal complexity to improve GHG emissions, suggesting that equivocality is likely not an issue in this complexity dimension.

As expected, vertical and spatial complexity are problematic for supply chain GHG emissions. This result is particularly consistent for vertical complexity, where the negative effects persist even discounting focal firms' GHG emissions. This means that increasing vertical complexity not only increases direct emissions but also strongly affects indirect emissions. The reduction of equivocality seems to play a key role in this dimension, consistent with the idea that its reduction can facilitate information-processing at each level of the supply chain (Akhavan and Zvezdov, 2021; Dahlmann and Roehrich, 2019). In spatial complexity, equivocality seems to be a serious problem that cannot be neutralised through the introduction of written guidelines. This could be due to different institutional and regulatory contexts that may hinder the possibility of successfully and quickly implementing a common guideline globally.

6.2 Theoretical contributions

Effective climate change mitigation strategies call for more systemic and holistic approaches in assessing the management of complex supply chains. The main contribution of this study is to go beyond the conventional theoretical approaches and, through the lens of OIPT, analyse if complex supply chain structures need to reconcile trade-offs between firm and supply chain GHG emissions. With respect to previous studies, we offer a novel perspective because by combining the sustainability literature on multi-tier and complex supply chains, we provide a more comprehensive way to analyse the effects of supply chain complexity in terms of information-processing on GHG emissions under different scopes. This study also places a strong emphasis on the need for the reduction of equivocality, which is still scarce in our field. The examination of supply chain complexity under an information-processing view leads us to think that equivocality can have a different nature according to the dimension of complexity analysed and the level of analysis considered. Finally, we contribute to the incipient literature that attempts to adopt methods to quantify the environmental impact of the supply chain. Although these methods are not yet fully standardised in the sense that they depend on the scope of the supply chain considered and on the different types of environmental performance measured (Mahapatra *et al.*, 2021; Tuni *et al.*, 2018), we provide some guidelines that can be used for future studies. We also draw attention to the need to consider the coverage of disclosed GHG emissions and of the sources used in the analysis.

6.3 Managerial recommendations

Our study has several managerial recommendations. First, we suggest to managers that they should not fear complex supply chain structures but rather learn to absorb their effects, because to a certain extent complexity is inevitable in today's business. In contrast to our initial predictions, generally, what is bad at the firm level is also bad at the supply chain level. This limits the need to balance potential trade-offs to the case of horizontal complexity, because it has positive effects at the firm level and not significant effects at the supply chain level. Consequently, it is important for managers to make a good selection of first-tier suppliers in terms of their capacity of intermediation with lower-tier suppliers, to facilitate information flow and processing either at the firm level or at the supply chain level. What they have to minimise is working with globally dispersed first-tier suppliers. These strategies should be accompanied by investments in information hubs or platforms making it possible to channel and coordinate information along the supply chain.

In the case of increasing vertical complexity, managers have to place priority on establishing mechanisms to reduce equivocality. Managers' efforts should focus on establishing routines for collecting information along the supply chain, making the information processing easier and oriented to continuous collective improvements and learning. This strategy would be ambidextrous because it would lead to GHG emissions advantages at both firm and supply chain level. One important issue that we wish to underline is that the use of information technologies alone would not be sufficient to reduce equivocality. Although it can promote transparency, equivocality reduction needs mechanisms to put in gear understanding processes that reduce ambiguities in information assimilation. In the case of increasing spatial complexity, information processing seems even more of a challenge since the use of written guidelines is not sufficient to reduce equivocality. Spatial complexity seems to require greater efforts by managers to promote systems to overcome the sense-making barriers within distant supply chain partners.

6.4 Concluding remarks and future research agenda

The premise of this study is that supply chain partners in complex structures need to better understand how change happens and increase their willingness to process information across boundaries to promote the transformation of supply chain systems. Preconditions for action encompass developing the capacity to ‘see’ the system, making sense of what is seen, and making connections across boundaries to then engage in purposeful actions towards transformations based on the new understanding of the system (Waddock, 2020). Transformation implies understanding complexity and how agents of transformation can function, which brings us to the concept of sense-making. This study partially explores the concept of sense-making (Weick, 1995) and also extends it to the supply chain structure. We emphasise the need to overcome sense-making limitations of supply partners in processing information, which may undermine the possibility of achieving lower GHG emissions. Sense-making is used to frame the concept of equivocality and suggests that supply chain partners need to have a good understanding of their progress in such a way as to shape common beliefs, attitudes, and mindsets that result in actions. In line with the revised paradigm in this domain (Nair and Reed-Tsochas, 2019), we suggest that future research should further develop the study of complex supply chain structures, strengthening their link with the analysis of multi-tier dynamics and the use of new technologies (e.g., artificial intelligence, blockchain among others) to measure and forecast GHG emissions along the supply chain in a way that reduces equivocality and facilitates their absorption.

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Figure 1. Conceptual model

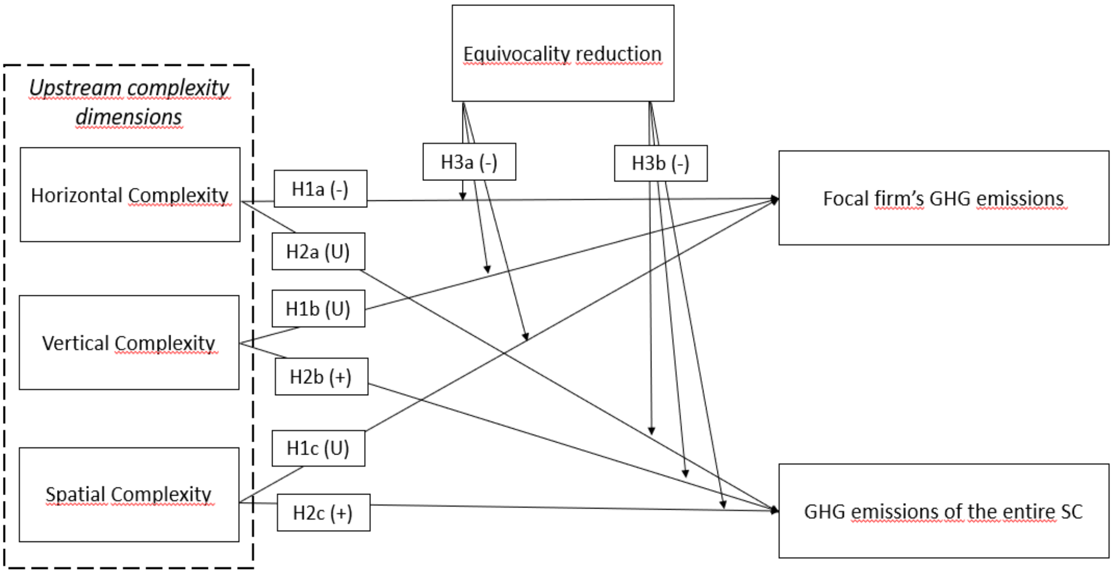

Table I. Data construction process

Steps	Reduction	No. of Firms
Start: SP500 firms, excluding those in the financial and real estate sectors		401
Step 1: Merge with Compustat	0	401
Step 2: Merge with Bloomberg	2	399
Step 3: Merge with Trucost	5	394

Table II. Variable descriptions

Variables	Measurements	Data Sources	References
Focal firm's GHG emissions	Relative GHG emissions of the focal firm (i.e., Scope 1)	Trucost	Scope 1 as defined by the GHG Protocol
Supply chain GHG emissions	Relative GHG emissions of the entire supply chain (i.e., sum of Scopes 1, 2, and 3)	Trucost	Novel—not empirically tested The Scopes as defined by the GHG Protocol
Horizontal complexity	Number of direct suppliers of the focal firm (i.e., first-tier suppliers)	Bloomberg	Adhikary et al. (2020), Bode and Wagner (2015), Sharma et al. (2020)
Vertical complexity	Average number of second-tier suppliers per first-tier suppliers	Bloomberg	Adhikary et al. (2020), Lu and Shang (2017), Sharma et al. (2020)
Spatial complexity	Total number of countries of the first-tier supplier based on their headquarters	Bloomberg	Lu and Shang (2017)
Equivocality (written guidelines)	The focal firm has/has not a suppliers' guideline that explicitly encompasses climate change issues.	Bloomberg Firms' reports	New—not empirically tested
No. of customer firms	Total number of customer firms	Bloomberg	Bozarth et al. (2009). Lu and Shang (2017)
No. of products	Total number of family products	Bloomberg	Bozarth et al. (2009), Lu and Shang (2017)
Carbon disclosure	Percentage of GHG emissions disclosure reported by the focal firm	Trucost	New—not empirically tested
Climate advanced capabilities	Firms has/has not developed or launched products which address future impact of climate change or/and which mitigate the customers' contribution by reduced GHG emissions	Bloomberg	New—not empirically tested
Size	Natural logarithm of total asset	Compustat	Dong et al. (2020)
Profitability	Return on assets (ROA)	Compustat	Adhikary et al. (2020), Sharma et al.

			(2020)
Production efficiency	Ratio of sales-to-production resources (i.e., plant, property, and equipment) for each firm compared to its industry defined at the four-digit NAICS level	Compustat	Lu and Shang (2017)
Age	Number of years since its foundation	Compustat	Adhikary et al. (2020), Bode and Wagner, Sharma et al. (2020)
Market share	Percentage of the firm's sales over the total industry sales at four-digit NAICS level	Compustat	Lu and Shang (2017)
R&D intensity	Ratio of research and development expenses to sales	Compustat	Dong et al. (2020)
Superior IT	Firm are\are not listed in InformationWeek Elite 100 (i.e., Top 100 IT quality firms)	InformationWeek	Bharadwaj (2000)
Supplier dependency	Percentage of supplier's sales to the focal firm over total supplier sales (Top supplier firm)	Bloomberg	Kim and Henderson (2015)
Customer dependency	Percentage of customer's cost of goods provided by the focal company (Top customer firm)	Bloomberg	Kim and Henderson (2015)

Table III. Random effects regressions on the GHG emissions at focal firm level

	Focal firm's GHG emissions	Focal firm's GHG emissions	Focal firm's GHG emissions
Horizontal complexity	-0.0251***	-0.0250***	-0.0230**
	(0.008)	(0.009)	(0.010)
Vertical complexity	0.2163	0.2003	0.2095
	(0.145)	(0.148)	(0.148)
Spatial complexity	0.8132**	0.8171***	0.7966***
	(0.316)	(0.299)	(0.302)
Vertical complexity^2		0.0002**	0.0002**
		(0.000)	(0.000)
Spatial complexity^2		0.0000	0.0001
		(0.002)	(0.003)
Equivocality	-0.7288**	-0.7184**	-0.7651*
	(0.369)	(0.362)	(0.427)
Horizontal complexity x Equivocality			-0.0017
			(0.003)
Vertical complexity x Equivocality			-0.0099*
			(0.006)
Spatial complexity x Equivocality			0.0355
			(0.040)
No. of customer firms	-0.0042*	-0.0042*	-0.0046**
	(0.002)	(0.002)	(0.002)
No. of products	0.2631*	0.2620*	0.2719*
	(0.143)	(0.143)	(0.144)
Carbon disclosure	-0.0205**	-0.0209**	-0.0209**
	(0.009)	(0.009)	(0.009)
Climate advanced capabilities	-4.5668**	-4.5169**	-4.4371**
	(2.144)	(2.160)	(2.166)
Size	-1.1769*	-1.1778*	-1.2305*
	(0.669)	(0.678)	(0.684)
Profitability	-2.4931***	-2.4325**	-2.4533***
	(0.967)	(0.947)	(0.945)
Production efficiency	0.5216*	0.5410*	0.5097*
	(0.310)	(0.315)	(0.302)
Age	-0.0072	-0.0072	-0.0076
	(0.021)	(0.021)	(0.021)
Market share	-0.0404***	-0.0428***	-0.0429***
	(0.015)	(0.015)	(0.016)
R&D intensity	-4.9118**	-4.6914*	-4.8269**
	(2.370)	(2.405)	(2.389)
Superior IT	-1.1623	-1.1888	-1.1908
	(0.850)	(0.860)	(0.873)
Supplier dependency	-0.0129	-0.0138	-0.0144
	(0.009)	(0.009)	(0.009)
Customer dependency	-0.0824**	-0.0817**	-0.0836**
	(0.033)	(0.033)	(0.033)
Horizontal complexity residuals	0.0235***	0.0234***	0.0227**
	(0.008)	(0.009)	(0.009)
Vertical complexity residuals	-0.2235*	-0.2302*	-0.2302*
	(0.135)	(0.137)	(0.138)
Spatial complexity residuals	-0.7811***	-0.7840**	-0.7862**
	(0.303)	(0.311)	(0.313)

Notes: N=1,172 observations (2016-2018) for 394 SP500 firms. Robust standard errors are reported in parentheses. Industries and year dummies are included in the models, but they are not reported.

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table IV. Random effects regressions on the GHG emissions of the entire supply chain

	Supply chain GHG emissions	Supply chain GHG emissions	Supply chain GHG emissions
Horizontal complexity	-0.0261	-0.0221	-0.0226
	(0.020)	(0.021)	(0.022)
Vertical complexity	0.4743**	0.4734**	0.4773**
	(0.231)	(0.232)	(0.231)
Spatial complexity	1.3693**	1.3546**	1.3457**
	(0.560)	(0.566)	(0.584)
Horizontal complexity^2		-0.0000	-0.0000
		(0.000)	(0.000)
Equivocality	-0.8559**	-0.8552**	-0.8518
	(0.411)	(0.412)	(0.869)
Horizontal complexity x Equivocality			0.0035
			(0.005)
Vertical complexity x Equivocality			-0.0199**
			(0.009)
Spatial complexity x Equivocality			0.0216
			(0.071)
No. of customer firms	-0.0085**	-0.0085**	-0.0095**
	(0.004)	(0.004)	(0.004)
No. of products	0.6543***	0.6575***	0.6724***
	(0.245)	(0.245)	(0.247)
Carbon disclosure	-0.0357**	-0.0358**	-0.0353**
	(0.016)	(0.016)	(0.016)
Climate advanced capabilities	-6.3929**	-6.3793**	-6.0520**
	(2.536)	(2.539)	(2.541)
Size	-1.5173	-1.5258	-1.6045
	(1.199)	(1.202)	(1.198)
Profitability	-2.7653	-2.7452	-2.7411
	(1.721)	(1.722)	(1.718)
Production efficiency	1.2510**	1.2648**	1.1854**
	(0.593)	(0.602)	(0.599)
Age	-0.0206	-0.0207	-0.0212
	(0.028)	(0.028)	(0.028)
Market share	-0.0351	-0.0352	-0.0358
	(0.027)	(0.027)	(0.027)
R&D intensity	-7.4653*	-7.4377*	-7.4839**
	(3.873)	(3.902)	(3.815)
Superior IT	-2.1259*	-2.1544*	-2.1449*
	(1.240)	(1.256)	(1.269)
Supplier dependency	-0.0239	-0.0238	-0.0251
	(0.017)	(0.017)	(0.017)
Customer dependency	-0.1070**	-0.1063**	-0.1098**
	(0.045)	(0.046)	(0.045)
Horizontal complexity residuals	0.0291*	0.0290*	0.0272*
	(0.016)	(0.017)	(0.015)
Vertical complexity residuals	-0.4808**	-0.4800**	-0.4752**
	(0.231)	(0.232)	(0.231)
Spatial complexity residuals	-1.1634**	-1.1581**	-1.1509**
	(0.528)	(0.531)	(0.532)

Notes: N=1,172 observations (2016-2018) for 394 SP500 firms. Robust standard errors are reported in parentheses. Industries and year dummies are included in the models, but they are not reported.

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table V. Control function regressions for upstream complexity

	Horizontal complexity	Vertical complexity	Spatial complexity
Peers' horizontal complexity	0.7236***		
	(0.162)		
Peers' vertical complexity		1.2201***	
		(0.454)	
Peers' spatial complexity			0.4658***
			(0.113)
World's most admired firms (*Fortune*)	8.0152	-3.0903*	1.7117***
	(9.124)	(1.755)	(0.544)
Uncertainty environment (*Nasdaq*)	5.2062	0.9374	0.4906
	(10.103)	(2.041)	(0.716)

Notes: N=1,172 observations (2015-2017) for 394 SP500 firms. Only the variables used as instruments to the complexity dimensions (i.e., peers' complexity dimensions, belonging to the list of most admired firms and being traded in Nasdaq) are reported. The variables included in the GHG emission models, except the upstream complexity dimensions variables, are also added in these control function regressions, but they are not shown.

*** p<0.01, ** p<0.05, * p<0.1