Firms' eco-innovation and Industry 4.0 technologies in urban and rural areas

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Abstract

We investigate the extent to which the firms' propensity to eco-innovate, adopt Industry 4.0 (I4.0) technologies and leverage them to eco-innovate varies with their location. We maintain that urban firms should be more prone to eco-innovate and adopt I4.0 technologies than rural ones, and more capable to make the latter functional to the former. Using a large sample of European firms, we test and confirm these hypotheses only partially. Firms in rural areas display a higher capacity to eco-innovate notwithstanding their lower digital propensity. However, an urban location reinforces the eco-innovative impact of digital technologies, irrespectively from its size.

Keywords: digital technologies, eco-innovation, twin transition, rural and urban areas.

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1. Introduction

At a time in which the net-zero transition is an imperative to avoid catastrophic climate change consequences, the advancement of the Industry 4.0 (I4.0) is posing new environmental threats and opportunities. On the one hand, the diffusion of new digital technologies has been having harmful consequences on rare input materials depletion, energy demand and material consumption, electronic waste generation and disposal, and eventually carbon footprint (Schwarzer and Peduzzi, 2021; Jones, 2018). On the other hand, I4.0 technologies are offering important opportunities to improve the green efficiency of current production and consumption modes and to facilitate environmental innovation (Barteková and Börkey, 2022; Sareen and Haarstad, 2021). In brief, as recognised with respect to the previous wave of ICT (Faucheux and Nicolaï, 2011), digital technologies can be "green-digital" and "digital-for-green". These are in fact the two sides, green and digital, of what policy makers are evoking as a "twin transition" (i.e., green & the digital) (EC, 2020; Muench et al., 2022):[1] a manifold and complex process, which requires reduction for the sake of analytical tractability.

Focusing on the digital-for-green side,[2] nearly 50% of the CO2 emissions reduction for the net-zero-transition by 2050 is expected from not-yet-existing cleaner technologies (IEA, 2021), which makes firms' eco-innovation (EI) a crucial leverage of environmental sustainability. Therefore, in the context of the twin-transition, it becomes important to investigate to which extent the new wave of digital technologies can be harnessed by firms for the sake of EI (Andersen et al., 2021). Following a standard definition, EI can be meant as the "production, assimilation or exploitation of a product, production process, service or management or business methods that is novel to the firm [or organization] and which results, through-out its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives" (Kemp and Pontoglio, 2007, p. 10).

Despite the hype about the twin transition, the research about it has been empirically undertaken only recently and, through some few and (at the time of this writing) still unpublished applied works, it has started showing that digitalisation can make firms more eco-innovative (Montresor and Vezzani, 2022; Kesidou and Ri, 2021; Demirel et al., 2022). Investing and/or adopting I4.0

[1] This is a companion notion of that of a 'green and digital transformation', also used by European politicians (Ministerial Declaration, 2021).

[2] The green-digital side will be not addressed in this paper and the interested reader is referred to, among the others, Patsavellas and Salonitis (2019).

technologies is argued and found to increase the firms' capacity to take environmental action, green-growth strategies, and eco-innovate with interesting nuances. Among these, little if no attention has been paid to the spatial context in which the "twinning companies" are located, with resulting scant knowledge about the places where the twin-transition could be more favourable. This is connected to the fragmented way in which the geography of EI has been generally investigated so far. Indeed, the spatial analysis of EI has been undertaken along heterogeneous and loosely connected research streams, which have been differently limited by the trade-off between the need of detailed information of firm-based analyses and the possibility to perform systematic studies on a large set of countries or territories (Losacker et al., 2021). This is even more so in the empirical investigation of the relationship between firms' EI and digitalization, which has remained so far largely aspatial. Given the way in which the green and the digital transitions are unfolding across places, this is a quite unfortunate gap. Along both transitions, regional disparities are in fact emerging in capabilities and outcomes with the risk of making the transitions uneven and "unjust" (Newell and Mulvaney, 2013), also and above all in the contraposition between urban and rural areas (Traversa et al., 2022; Szeles, 2018; Wang et al., 2022), on which we focus in the present paper. Rural areas have historically suffered from a structural delay with respect to urban ones in facing transitions, like the (de-)industrialization, financialization and globalization of modern economies (Woods, 2016; Zhou and Li, 2021). However, a recent EC Communication about "a long-term vision for the EU's rural areas" (EC, 2021) has envisaged that the green and the digital transitions are offering unprecedent opportunities to these areas. Having a natural primacy in the sustainable production of food, the management of natural resources, and the preservation of landscape and biodiversity, rural areas can in fact take stock of the roll-out of new digital technologies to extend their green development opportunities beyond agriculture, farming and forestry. In brief, as the Communication states, it is expected that "rural areas are active players in the EU's green and digital transitions" (cit., p.2). This is particularly the case of firms based in rural areas, on which we will focus in the paper by contrasting them with those in urban areas. By following a relational (micro) - rather than territorial (meso) - perspective to the analysis of peripheral (eco-) innovative activity (see Eder, 2019, p.127), we will approach it by retaining that firms' (atomistic) inputs and initiatives are key in the absence of an agglomerated, dense, and vibrant innovative environment. Investigating the extent to which digitalisation affects EI in rural versus urban firms, can help understanding the new opportunities that the twin-transition is posing to different territories and designing suited place-based policies (Rodríguez-Pose, 2017).

To contribute filling the spatial gap in the analysis of the twin transition, we study the extent to which firms' digitalization, their introduction of EI, and their capacity to link the two vary with the urban versus rural nature of their location. To do that, we take stock of a new set of questions posed by the EC-Eurobarometer (486) about the rural rather than urban location of the surveyed firms. Although at the price of a lower precision with respect to alternative methodologies to investigate territorial aspects (see Section 3), these questions enable us to report at the territorial level, the wide set of primary data that the survey collects and anonymously discloses for a large sample of European firms.

The rest of the paper is structured as follows. In the next section, we overview background studies and develop our research hypotheses. Section 3 presents the dataset and the econometric strategy of our empirical application. Section 4 illustrates the results and Section 5 discusses its implications. Finally, Section 6 concludes.

2. Background studies and research hypotheses

The academic evidence about the environmental implications of I4.0 technologies is already quite wide (Kumar et al., 2020; de Sousa Jabbour et al., 2018). A large gallery of case studies has shown that I4.0 technologies can improve the efficiency of firms in using energy, water, and natural resources, as well as in generating and disposing waste.[3] However, the theoretical and empirical work on digitalization in the context of sustainability transitions is still at an incipient stage (Andersen et al., 2021, p. 96), especially in looking at "digitalization […] as a driver of environmental innovation" (Sareen and Haarstad, 2021, p.94).

Going beyond the available case-based evidence, the extent to which digitalization can increase the firms' capacity to eco-innovate has been only limitedly investigated on a systematic basis. With respect to a large sample of Italian firms, Montresor and Vezzani (2022) have shown that, with some nuances, digital investors have a higher propensity to act for the environment and to redesign their production process and/or adopt new production models accordingly. Working on a sample of over 1,000 SMEs in the UK, Kesidou and Ri (2021) have found evidence of manifold synergies between digitalisation and changes in production/processes to reduce carbon emissions. Using a large sample of SMEs from 39 countries, Demirel et al. (2022) have shown that a well-defined

[3] Just to make an example, novel sensor-based technologies enable firms to monitor in real and continuous time their machine utilization and the relative energy need, so that to act on it in a smart way.

digitalisation strategy can enhance the growth impact of EI. Despite important specificities, this recent evidence generally supports a Schumpeterian view in which, mainly thanks to their general-purpose nature (GPT), digital technologies provide firms with "interfaces" to better combine and recombine the complex set of knowledge modules required to eco-innovate (Montresor and Vezzani, 2022; Cicerone et al., 2022; Montresor and Quatraro, 2020).

As anticipated, in the few studies mentioned above, the role of the spatial context in which firms are located is not considered. This is particularly the case of the urban versus rural nature of the areas in which firms are based, which is the focus of this work.

In regional and economic geography studies, firms based in large cities are commonly expected and found to be more innovative than non-urban ones in general technological terms (Feldman and Kogler, 2010; Bettencourt et al., 2007; Carlino and Kerr 2015). Especially with respect to radical and "unconventional" ones (Berkes and Gaetani, 2021), innovations have been even claimed to "require cities" to occur (Florida et al., 2017, p. 93) due to the crucial role that agglomeration economies of different kinds (i.e., input sharing, labour matching, and knowledge spillovers) have for their unfolding (Duranton and Puga, 2004). Despite this consensus, recent case studies have shown that firms innovate successfully also in rural and peripheral areas (Grillitsch and Nilsson, 2015; Fritsch and Wyrwich, 2021a). In these areas, the lack of external agglomeration economies is in fact often compensated by more efficient internal organisations, wider networks, and higher absorptive capacity. Most studies on the relationship between innovation and city-size do not explicitly retain rural areas and avoid comparisons between cities and non-agglomerated areas. However, using cross-country data, Fritsch and Wyrwich (2021b) have shown that "there is no general tendency that inventors in large cities are more productive […] when compared to inventors in rural areas" (p. 104237).

As far as firms' EI is concerned, the distinction between urban and rural areas has been only scantly and recently considered (Galliano et al., 2017; 2022). At the outset, given the advantages of agglomeration economies, it would appear natural to conclude that firms in urban areas are more eco-innovative than rural ones. Consistently with this expectation, there is evidence that EIs are facilitated by Marshallian specialisation economies entailed by co-located firms within the same industry (Antonioli et al. 2016; Cainelli et al. 2011, 2012; Mazzanti and Zoboli 2008; Galliano et al., 2022). An urban location can be expected to facilitate firms' EI also passing through the Jacobsian variety of the knowledge its actors generate and disseminate (Florida et al., 2017). Urban areas normally host a variety of industrial and non-industrial players (e.g., public and private research organisations), among which the cross-fertilisation of ideas, facilitates the process of knowledge recombination at the basis of EI (Montresor and Quatraro, 2020). All in all, it would appear natural to expect the following first research hypothesis:

Hp1: *Firms in urban areas have a higher capacity to eco-innovate than in rural ones.*

While this is our expectation, we should retain that also rural areas can represent a basin of EI for their firms. As rural business studies have shown, rurality does not entail the absence of innovativeness at all. Rural areas are rather marked by a more hidden kind of innovation process largely relying on experience-based and synthetic know-how, in which firms innovate more slowly and less technologically, following a "Doing, Using and Interactive" mode (Jensen et al., 2007). The same mode of innovating extends to the firms' EI (Galliano et al., 2019; Marzucchi and Montresor, 2017), for whose occurrence rural areas benefit from the additional advantage of local natural resources. For example, local soya crops could facilitate EI in biodiesel, while coasts and solar exposure could make rural firms more prone to EI in the energy sector. Furthermore, rural areas typically host SMEs, micro and individual firms that have a higher capacity to create and mobilise networks of local actors, who can collaborate, share and make a collective use of individual environmental resources and green assets (Grillitsch and Nilsson 2015; Esparcia 2014). In the light of these considerations, the expected EI advantage of urban over rural firms is not guaranteed and the test of Hp1 will help us to assess it.

The distinction between urban and rural areas is also relevant in looking at the firms' adoption of I4.0 technologies and, more importantly for our focal research question, at their enabling role of firms' EI. A wide literature about the digital urban-rural divide recognises the higher digitalisation of the former and investigates both its determinants and regional effects (among the latest studies, see Cowie et al., 2020; Guzhavina, 2021; Norris, 2020; Jamil, 2021; Antonietti et al., 2023). In extreme synthesis, such a gap is traced back to a twofold delay that rural areas show with respect to urban ones in terms of both digital hardware (e.g., broadband diffusion) and software use (e.g., basic digital skills) (EC, 2021). With few exceptions (like Holl and Rhama, 2022), firm-based literature usually refers to regional case-studies and to limited comparative analyses of firms in different contexts (i.e., regions hosting both urban and rural areas). Still, what emerges from this research widely suggests that an urban-rural digital divide should be detected also on a systematic basis and reflected in the firms' adoption of I4.0 technologies, leading us to put forward the following second hypothesis:

Hp2: *Firms in urban areas have a higher capacity to adopt I4.0 technologies than in rural ones.*

The urban-rural digital divide is also crucial in affecting the firms' capacity to render digitalisation functional to the introduction of EI. Drawing on the recent studies surveyed in Section 2, and on their background arguments (see Montresor and Vezzani, 2022), we do expect that digitalisation increases the firms' capacity to eco-innovate across the board, both in urban and rural areas. However, while the I4.0 revolution can be expected to be as beneficial in rural as in urban areas, its diffusion in the former has been and is hampered by relevant infrastructural and cultural barriers (Cowie et al., 2020; Roberts and Townsend, 2016). These barriers could in turn be an impediment to the firms' capacity to fully exploit the innovative contribution that I4.0 technologies can bring to the green transition. The lack of a (urban) digital culture, for example, along with modest digital skills across (shorter and simpler) value-chains, can make rural firms less capable, if not even more reluctant, to retain digitalisation among the drivers of new environmentally sustainable processes and products. In the "community-led" innovation style of urban areas (EC, 2021), the attention to greener digital technologies (e.g., worries for the use of natural resources in producing and adopting them) can overcome the attention to their green opportunities (Faucheux & Nicolaï, 2011). In addition to this barrier-based argument, all the background studies mentioned at the beginning of this section reveal that firms' EI benefit from digitalisation in the presence of dense digital ecosystems. These are eco-systems marked by a scale and scope of digital activities, and by a set of interacting local stakeholders and networks, which the digitalisation literature has shown to require large markets, typically hosted in urban areas (Forman et al., 2005). On the contrary, the numerous "white spots" that still characterise rural areas in terms of infrastructure (e.g., transport and communication) and competences (e.g., digital and non-digital skills) make these digital eco-systems hard to be built locally and employed for eco-innovating. By combining the previous arguments, we put forward our third, twofold hypothesis about the I4.0-EI link:

Hp3a: *Firms leverage I4.0 technologies for eco-innovating.*

Hp3b: *Firms in urban areas leverage I4.0 technologies for eco-innovating more than rural ones.*

3. Empirical analysis

3.1. Data and variables

Using firm micro-data from the EU-Flash-Eurobarometer-486 on "SMEs, Start-ups, Scale-ups and Entrepreneurship",[4] we test our hypotheses on a large sample of about 14,000 firms across 36 European countries: the EU28 (pre-Brexit) plus 8 extra-EU countries (Turkey, Croatia, Makedonia, Serbia, Norway, Iceland, Bosnia and Herzegovina and Kosovo), with respect to the period 2016-2019.[5] Despite its cross-sectional nature, which prevents us from claiming causality, this is the first study that searches for a cross-country, systematic correlation between firms' EI and digital technologies by retaining the nature of their location.

3.1.1 Dependent variable

Our main dependent variable is a dummy, EI_i, which takes value 1 if firm *i* has declared to have introduced an "innovation with environmental benefits, including energy and resource efficiency" (Q19 in the survey), which we consider as an eco-innovation in general terms. Unfortunately, the survey does not enable us to retain the richness of aspects to which the definition of EI usually refers (see Section 1). Still, our dependent variable allows us to refer to benefits of environmental nature that firms had from innovating, and that are an integral part of their EIs.

In the robustness checks (see Section 4.2), we also investigate if digitalisation can make firms more eco-innovative in a strictly technological sense, and we build up another dummy, EI_Tech_i, which takes value 1 if the EI introduction is concomitant with a product and/or process innovation. On the contrary, the survey prevents us from disentangling the degree of novelty of the declared EI, which could be new to the focal firms to a different extent (e.g., only to the firm, to its region, or to the world). However, rather than a limitation, this feature of the questionnaire allows us to detect rural innovations that normally fall out of the radar using stricter meaning of technological novelty, like with patent data.

3.1.2 Main regressors

The focal regressors of our analysis are represented by the firms' adoption of I4.0 technologies and by the localisation of firms.

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[4] While the Eurobarometer Research Report focuses on SMEs only (https://op.europa.eu/en/publication-detail/-/publication/fa52df25-0846-11eb-a511-01aa75ed71a1/language-en), our analysis makes use of the entire sample of the relative dataset, including large firms.

[5] The set of countries has been driven by the opportunity of having more homogeneity across the interviewed firms, especially with respect to the declarative question about the firm's location (urban vs. rural). This country set will be extended among the robustness checks (Section 4.2).

As for the former, we build up a dummy, $DIGIT_i$, taking value 1 in case firm *i* has adopted at least one of the I4.0 technologies listed by the Eurobarometer: artificial intelligence, cloud computing, robotics, smart devices, big data analytics, high speed infrastructure, and blockchain (Q23); and 0 otherwise. Given the high share of micro and small firms (80%) in our sample, we deem the adoption of at least one of them a suitable indicator of their digital vs. non-digital I4.0 status. Non-digital firms are in fact nearly one-third of our sample and, in line with other evidence (Montresor and Vezzani, 2022), even fewer are the firms that have adopted artificial intelligence or blockchain technologies.

In addition to the standard list of variables used in previous surveys, the Eurobarometer-486 includes a new distinguishing question that enables us to detect the type of location in which a firm is based. While not reporting the geographical coordinates or addresses of the surveyed firms, the Eurobarometer-486 asks firms whether they are located in rural or urban (small and large) areas (Q 8). This is of course a less refined way to locate firms than through objectively established gridded population data, which are currently used to map functional urban areas (Dijkstra et al., 2019). Given the nature of the survey, interviewed firms might subjectively refer to areas of heterogeneous size and characteristics even when tagging the same response item. However, being asked about their location through an extended and varied kind of survey, the interviewed firms can be expected to respond to it comprehensively, by retaining both the geographical (e.g., remoteness) and functional (e.g., infrastructural endowment) nature of their location (Eder, 2019), and to classify it in a relatively homogenous manner.

We use the answers to location questions to first calculate a dummy, $Urban_i$, which distinguishes firms in urban from those in rural areas (the dummy $Rural_i$ is its complement). We then unpack the *Urban* dummy in other two dummies – $Large\_Urban_i$ and $Small\_Urban_i$ – accounting for the size (large or small) the interviewed firm *i* has declared for its urban location. To control for other location characteristics that might influence firms' EI or I4.0 adoption, we include in the regressions information on whether firms are located in an industrial area and/or near a border with another country (both options are non-mutually exclusive with respect to the rural-urban location). Extending the arguments of Section 2, we expect the effects of the three hypotheses to hold true to a greater extent with respect to large than small urban areas.

Figure 1 shows the distribution of the share of rural firms across our sample of European countries. This is marked by an appreciable heterogeneity (see Appendix A on-line). While the average share is about 10%, the incidence of rural firms is much higher (lower) in Norway and Austria (in Italy, Portugal, Greece and Eastern countries).

[FIGURE 1 ABOUT HERE]

3.1.3 Other regressors

Following the "regulatory, demand-pull, and technology-push approach" that normally drives the investigation of EI (Horbach et al., 2012), we plug in the empirical analysis three regressors. First, we proxy the role of environmental regulations with a dummy, *Green policy support$_i$*, which takes value 1 if firm *i* declares to have received policy support to become more sustainable (Q16). As for science-push factors, we introduce the dummy *Patent holder$_i$*, taking value 1 if firm *i* has at least one patent application. As for demand-pull drivers, the dummy *Export$_i$*, denoting if firm *i* export goods or services, tells us whether it is present in the international markets.

We finally control for some structural variables like *size$_i$*, captured through a series of dummy variables for micro (2-9), small (10-49), medium (10-49), and large (250+) firms; *age$_i$*, calculated by subtracting the survey-year to the year of firm establishment and transforming it in logarithm; *Family owned$_i$*, captured by a dummy for the relative status. We also control for country and industry fixed effects with the inclusions of industry- (at the NACE 1 digit) and country-dummies.

Table 1 displays the descriptive statistics for our sample of 14,332 firms, while Table A2 in the Appendix shows that the correlations among covariates do not highlight possible collinearity issues.

[TABLE 1 ABOUT HERE]

3.3. Econometric strategy

Our econometric analysis is based on a seemingly unrelated bivariate probit model of the following form:

$$EI_i = \beta_1 Urban_i + \beta_2 DIGIT_i + \beta_3 X'_i + u_{2i} \quad (1)$$

$$DIGIT_i = \gamma_1 \, Urban_i + \gamma_2 \, X'_i + u_{1i} \quad (2)$$

$$\begin{pmatrix} u_{1i} \\ u_{2i} \end{pmatrix} \sim N \left\{ \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{bmatrix} 1 & \rho \\ \rho & 1 \end{bmatrix} \right\} \quad (3)$$

where EI_i, $DIGIT_i$ and *Urban$_i$* stand for the above defined focal variables, vector *X'* contains our control variables, and u_{1i} and u_{2i} are the error terms of equations (1) and (2), which can be eventually correlated. Indeed, due to possible complementarities in their introduction and/or common unobservable factors, EIs and digital technologies may not be mutually independent choices and, in case the correlation (ρ) between the error terms (u_{1i} and u_{2i}) is statistically different from 0, the relative two equations should not be estimated with two separate probit models (Green, 2018). As expected, the correlation coefficient (ρ) reported in Table 2 (see Section 4), as well as in all the robustness checks we have implemented (see Appendix B), confirms this is the case across all the model specifications and supports the choice of our econometric strategy.

The test of Hp1 and Hp2 is based on the results for the coefficients, β_1 and γ_1, of the $Urban_i$ dummy, which we use against the $Rural_i$ benchmark in equations (1) and (2), respectively. To investigate whether the same hypotheses (and Hp3) are sensitive to the size of the urban areas contraposed to rural ones, we re-estimate our model by substituting $Urban_i$ with the two dummies, $Urban\_Small_i$ and $Urban\_Large_i$. Finally, to test our Hp3, we first focus on the β_2 coefficient for $DIGIT_i$ in equation (1) (Hp3.a). We then estimate an augmented version of our model, adding in equation (1) the interaction term between $DIGIT_i$ and $Urban_i$ (and $Urban\_Small_i$ and $Urban\_Large_i$) (Hp3.b). Should the coefficients β_2 and that of this interaction be significantly positive, Hp3 would be confirmed.

As is usually the case, our focal *DIGIT* regressor could be affected by potential endogeneity descending from both reverse causality (i.e., eco-innovative firms more prone to get digital) and unobserved heterogeneity (i.e., factors relevant both for EI and DIGIT). To account for this issue, and retaining the binary nature of $DIGIT_i$, we follow Wooldridge's (2010, Section 15.7.2) approach and use as an instrumental variable, the dummy $No\_Digitalisation\_Interest_i$; this variable takes value 1 if the focal firm has declared "to have no interest at all in digitalisation" in responding about the barriers to the relative adoption (Q21). As the effect of this last variable on EI can only pass through its impact on *DIGIT*, we omit it from equation (1). Conversely, as it arguably does not directly affect $DIGIT_i$, we exclude the dummy *Green policy support* from equation (2).[6]

4. Results

4.1 Baseline estimates

[6] As we will see (Section 4.2), in a robustness check we deal with the issue that the (non) absence of interest in digitalization could be considered as a characterizing feature of the ICT industry, by dropping the relative firms. Furthermore, in order to check for the absence of correlation between $DIGIT_i$ and $Green\ Policy\_support_i$, we have estimated an alternative version of the seemingly unrelated bivariate probit model by adding this last variable to equation (1). As expected, results obtained in this way – available from the authors up request – are in line with those presented in Section 4, and the coefficient associated with $Green\ policy\_support_i$ in equation (1) is not significant.

As an introduction to the estimation results, Appendix A (on-line) reports some descriptive statistics for the dependent variable (*EI*), the focal regressor (*DIGIT*) and their relationship. As expected, the share of digital adopters is lower in rural areas, while the opposite is unexpectedly true for eco-innovative firms (Table A1). The share of rural firms that eco-innovate is higher than that of urban ones across the great majority of the retained sectors (Figure A2), including in manufacturing. Quite interestingly, firms located in rural areas show a higher EI propensity that extends also to production and transformation processes and is not limited to service sectors and utilities. The larger share of eco-innovative rural firms is particularly marked in the energy sector, in which the advantages of natural resources and biodiversity seem to matter, and where the share of rural digital firms is also exceptionally larger than the digital urban one (Figure A3).

This preliminary evidence is somewhat counterintuitive and possibly at odds with what we hypothesized in HP1; thus, calling for further confirmation in a multivariate econometric framework. In fact, the higher EI propensity of rural firms could be possibly due to a different interpretation of what an innovation with an environmental benefit actually is across firms of different size. In particular, larger firms are usually more likely to be based in urban contexts and may tend to underestimate the extent to which they eco-innovate by disregarding activities/processes that are perceived as EI by smaller (and thus probably rural) firms. However, this explanation is not supported by the data: while rural firms tend to be smaller compared to urban ones, it is noticeable how larger firms show a higher rather than lower propensity to EI (see Table A3 in the Online Appendix). Furthermore, by including firm size and the sector of economic activity among the controls in all the specifications, we are able to test the effect of urban-rural location on the propensity to eco-innovate while ruling out these possible confounding factors.[7]

Coming to the econometric results, Table 2 reports the estimates of the seemingly unrelated bivariate probit model – with respect to *EI* and *DIGIT* in the first and second columns, respectively – by progressively incorporating in the baseline for *EI* (panel a), our focal regressor *DIGIT* (panel b), and its interaction with the urban location dummy (*Urban*) (panel c).

To start with, let us notice that the controls we have identified generally work as expected (see Table B1 in Appendix B on-line). Across all panels (a – c), a policy support to environmental sustainability makes firms' eco-innovating more probable, while the propensity to get digital

[7] See also Tables A5 and A6 in the Appendix for the distribution of firms across sectors and firm location, and for the share of firms that are eco-innovating by sectors and firm location.

expectedly decreases in the absence of an interest in digitalisation. Both the propensity to get digital and to eco-innovate significantly increase with firms' size: once again, larger firms are more rather than less likely to declare the introduction of EI (and DIGIT).

[TABLE 2 ABOUT HERE]

Coming to our hypotheses, urban firms display a lower propensity to eco-innovate than rural ones across the board. In all the specifications, the coefficients of $Urban_i$ for *EI* are significantly negative with respect to the benchmark (rural firms). This result does not support our Hp1 and in fact reverses it, revealing with respect to EI a "rural premium", which some rural business studies have previously recognised but with respect to standard innovation (Phillipson et al., 2019). In our analysis, this premium appears instead peculiar of the green realm and connected to the inner nature of EI. Indeed, as Table A1 (in the Appendix on-line) shows, unlike for EI, the share of firms that introduce product and/or process innovation in the absence of "environmental benefits" is significantly higher among urban firms.

Of course, the result for Hp1 might depend on a series of locational factors not covered by our data and that would deserve further scrutiny. For example, it might be linked to the increasing policy attention to rural innovation and sustainability in the EU (ERDF, 2019; EC, 2021), which can make the EI support more frequent in rural than urban firms. However, this is not supported by our data, as the share of firms that declared to benefit from a policy aid to sustainability does not differ between urban (8.7%) and rural (8.1%) areas. An explanation should thus be arguably found in the EI enabling conditions identified for rural areas, spanning from the availability of natural resources and biodiversity to the mobilisation of firm networks. These factors seem to more than compensate the disadvantages these areas arguably suffer in terms of lower agglomeration and infrastructural economies. However, urban agglomeration does not appear to provide firms in larger (urban) areas clear advantages either. As Table 3 shows, when the dummies $Large\_Urban_i$ and $Small\_Urban_i$ are used instead of $Urban_i$, their coefficients with respect to EI – still negative, consistently with results in Table 2 are not significantly different. The urban dimension does not seems to play a major role for firms EI, being the rural-urban dichotomy that matters. In absence of richer data, we can only hint that, across our wide set of countries, urbanisation diseconomies (e.g., higher congestion and pollution) and economies somehow mutually counterbalance and cancel out their effects on EIs by the resident firms.

[TABLE 3 ABOUT HERE]

Table 2 supports Hp2 by showing that urban firms are more capable and prone to adopt digital technologies than rural ones: *Urban*$_i$ is significantly positive in the second column of all the specifications (a – c). This provides further systematic and updated (to the I4.0) evidence about the existence of an urban-rural digital divide at the firm level across European countries. Furthermore, unlike for EI in Hp1, Table 3 suggests that this divide appears connected to the size of the hosting urban area, as it is more marked in the comparison between rural areas and large cities (e.g., metropolis). Across all its specifications (a – c), it is the coefficient of *Urban_Large* that reveals the highest-level significance, while *Urban_Small*$_i$ is significant only at the 10% level.

As far as Hp3 is concerned, panels (b) and (c) of Table 2 (and Table 3 too) reveal that *DIGIT* is significantly and positively correlated with *EI*, confirming that firms leverage I4.0 technologies for eco-innovating across the board, as from Hp3.a. Given the paucity of evidence about the functional use of digital technologies for the sake of EI, limited to appreciable samples of firms only in some specific countries (see Section 2), this is another important result about the pervasive existence of a twin-transition passing through EI. What is more, the result at stake reveals that this kind of twin-transition is accessible to rural firms too.

As for the second part of Hp3 (Hp3.b), Table 2 confirms that the twin transition at stake (digit-for-EI) works more for firms in urban than in rural areas: the interaction term *DIGIT*Urban* is significantly positive in panel (c). As we had envisaged, urban areas arguably host the infrastructures, skills and competencies that facilitate the constitution of eco-systems in which digital technologies can interoperate among them on a larger scale and can be more effectively exploited to eco-innovate. Still, by crossing this result with that about Hp1, it seems that the lower extent to which rural firms can use the digital leverage to eco-innovate is more than compensated by other rural EI-leverages, as discussed in Section 2. Indeed, as we will further elaborate in the discussion section, results from the test of Hp1 seem to confute the famous argument of "the city as innovation machine" (Florida et al., 2017) when coming to the green domain. On the contrary, they rather suggest that rural regions could contribute substantially to EI, possibly by being part of a larger constellation of places, with respect to which inter-agglomeration spillovers can replace agglomeration ones. In concluding the illustration of the baseline results for Hp3, it is interesting to notice that, by echoing what we found in testing Hp1, there is no apparent difference between the coefficients of the *DIGIT* interaction term with *Urban_Large* and *Urban_Small* in Table 3. While an urban eco-system is possibly more enabling of the EI effect of digital technologies, for the firms at stake this does not occur to a greater extent when such a digital eco-system is larger in size. Once more, this is somehow unexpected and points to the possible existence of urbanisation diseconomies vs. economies also in the twin-transition, on which future research should concentrate.

4.2 Robustness checks and additional results

The tables reported in the Appendix B (on-line) reveal that our baseline results are generally confirmed in a set of alternative specifications.

Firstly, the results we have obtained are robust when we run our model with a conditional recursive mixed process (CRMP) (Table B2) (Roodman, 2011), in which the endogenous regressor is instrumented recursively still on the basis of the variable $No\_Digitalisation\_interest_i$ (see Appendix B for more details). Indeed, this model strengthens our results against the potential endogeneity of our *DIGIT* regressor. Furthermore, to better control for it, we also run the CRMP by dropping from the sample the firms belonging to the information and communication sector, whose digitalisation interest is of course a characterizing feature, and results are still robust.

Secondly, baseline results are robust when we focus on EIs that firms introduce in the technological domain (*EI_Tech*), by developing new sustainable products and/or processes “with environmental benefits” (Table B3). Quite interestingly, this suggests that I4.0 technologies could help firms, not only in developing more sustainable innovative practices of a soft kind (i.e., green certificates and standards), but also and above all in devising new green products and processes. The fact that this occurs more in rural than in urban areas is of upmost importance for their future development (EC, 2021).

Thirdly, results are robust when we repeat our estimates with respect to the full sample of 40 countries of the Eurobarometer, including Brazil, Canada, Japan, and the US (Table B4). The presumable difference with which firms in these extra-European countries perceive and declare the nature of their location area does not affect our results.

5. Discussion

The set of results that we have obtained enable us to advance the current theoretical understanding of the firms' capacity to eco-innovate across different geographical contexts and is rich of policy implication.

To start with, the results we have obtained about the higher EI capacity of rural firms with respect to urban ones enrich the long-lasting debate about the importance of urbanisation for innovation (for recent contributions see Fritsch and Wyrwich, 2021; Berkes and Gaetani, 2021; Mewes, 2019). Contrasting the famous view of the "city as innovation machine" (Florida et al., 2017), the test of Hp1 suggests that, with respect to the green realm, not only cities are not "required to innovate" (ibidem) but that urban contexts could also represent less enabling contexts for that to happen. This result is more in line with an alternative view according to which innovation occurs, rather than in isolated urban contexts, within broader spatial systems composed by cities and less and/or not urbanised areas that interact among them leading to outcomes that are not necessarily hierarchical between the two typologies of space (Crescenzi et al., 2007). The use of metrics for innovation relying on patents may give too much weight on strict technological novelty, missing other types of (rural) innovations, and disadvantage rural locations if registration is attached to a head office (urban) address. Quite interestingly, the higher propensity of rural over urban firms in eco-innovating emerge across a wide set of countries.

The results related to the other two hypotheses of ours are also theoretically relevant. The endowment of digital technologies appears as an EI-enabler for firms, confirming a recent debate about the role of Industry 4.0 technologies in increasing the firms' dynamic capabilities in front of the green "reconfiguration" firms must face (Gupta et al., 2020; Laakso et al., 2021). However, the EI enabling role of the last wave of digital technologies appears more powerful in urban than in rural areas, revealing that the knowledge-recombinatory function that geography of innovation studies have recognised to these technologies in the green realm (Montresor and Quatraro, 2020; Cicerone et al., 2022), is in fact conditioned by the degree of urbanisation of the firms' location. In other words, it is not the simple local endowment of these technologies that facilitates firms' EI, but rather their constituting digital eco-systems that urban infrastructures are more capable to make it emerge (Veugelers, 2018).

As we will stress in the following section, this last result makes of digital policies for urban areas an important priority, also along their way towards the green transition. However, by providing an additional theoretical insight, it seems that in the development of environmental innovations, digital infrastructures and capabilities at the local level are less empowering than other EI leverages. As we said, these could be found in the endowment of natural resources and in the firms' capabilities of absorbing and integrating innovative knowledge they could lack internally and be forced to acquire externally. Indeed, as we have shown, while rural areas have to discount a digital gap, also in making Industry 4.0 technologies functional to EI, their eco-innovating capacity remains higher.

6. Conclusions

The few systematic analyses that have been performed so far using firm micro-data have shown that the I4.0 paradigm can provide firms with capabilities to develop new green technologies and render their production and business processes more environmentally sustainable. However, this micro-data-based evidence is still limited to few countries and, above all, has so far neglected the role of the spatial context in which firms are based. Given the disparities that both the green and the digital transitions are generating across places, possibly accentuating the peripherality of the "places that do not matter" (Rodríguez-Pose, 2018), this is a quite unfortunate gap.

In trying to fill this gap, we have taken stock of a new location-question contained in the EU Flash-Eurobarometer-486 and we have investigated, for the first time on a cross-country base, whether an urban rather a rural "declared" location can affect the capacity of the resident firms to eco-innovate, digitalise, and render their digitalisation functional to EI. In so doing, we have provided evidence to support the long-term vision that the EC has recently launched to render European rural areas "stronger, connected, resilient and prosperous by 2040" (EC, 2021), which foresees a series of flagship initiatives relying on the premise that "rural areas are active players in the EU's green and digital transitions" (cit., p.2).

Referring to a large sample of European firms with respect to the period 2016-2019, we have obtained a set of results, from which important policy implications can be drawn. As for the first result, about the higher EI propensity of firms in rural areas, given their pervasiveness (across EU and extra-EU countries), policy makers should retain that these areas could provide a stimulating basin of new eco-innovative solutions to be exploited in facing the net-zero-transition. Furthermore, given the notable win-win (environmental and economic) impact it has been recognised, EI can serve to reduce the gap that rural areas display with respect to urban ones in different domains, thus attributing to rural green policies a cohesive flavour. However, as firms appear less propense to eco-innovate where they should be the most - given the worse environmental performances (e.g., in terms of pollution and CO2 emissions) of urban areas - the implementation of urban green policies is possibly more important than rural ones.

Our second result, confirming previous fragmented evidence of a rural-urban digital divide, suggests that the actions envisaged by the EU Rural Action Plan to boost the digital transformation of rural areas are indeed of fundamental relevance. Indeed, as our third result has revealed, these digital actions can also make rural areas more eco-innovative.

Our third result is in fact possibly the most relevant. On the one hand, as firms' digitalisation seems to help firms with their eco-innovation, both in rural and urban areas, policy makers should retain and possibly rely on this green side effect in implementing digital policies (Montresor and Vezzani, 2022). On the other hand, as digitalisation seems to help firms' EI more in urban than in rural areas, digital policies could result less green-twinning in rural areas, whose EI capacity relies more on other non-digital leverages. This result supports what the EC has recommended to policy-makers as the "rural proofing" of local policies, and alert about a possible lower effectiveness of twin-transition policies in rural contexts compared to urban ones, which call for a better understanding of what actually work best in rural areas.

As usual, our study is not free from limitations that future research can try to address. First, knowing the kind of location (urban vs. rural) in which firms are based is only a bit of information about the socio-economic and agglomerative forces that it hosts. Their explicit consideration would definitively provide more accurate insights, but it would also require territorially granular data, not available so far unless for single/few countries (see Galliano et al., 2022). Second, despite the econometric techniques that we have adopted, the relationship we have identified between digital and EI through our cross-sectional application cannot be deemed causal. Longitudinal micro-data would be necessary but, once more, they are hard to get for large samples of territorial contexts. In both cases, future datasets could serve to support and possibly refine the results of our investigation.

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Figures and Tables

Figure 1

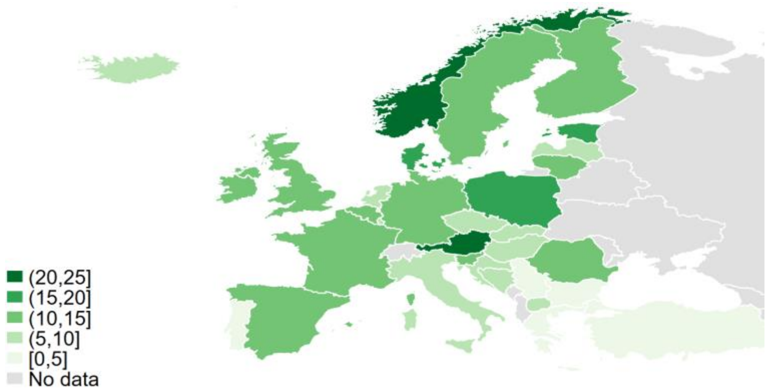

Figure A1

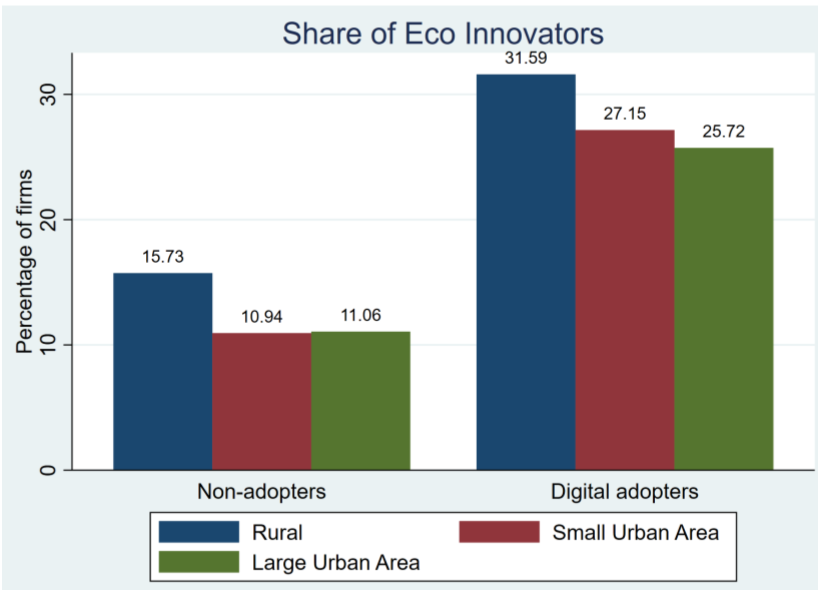

Figure A2

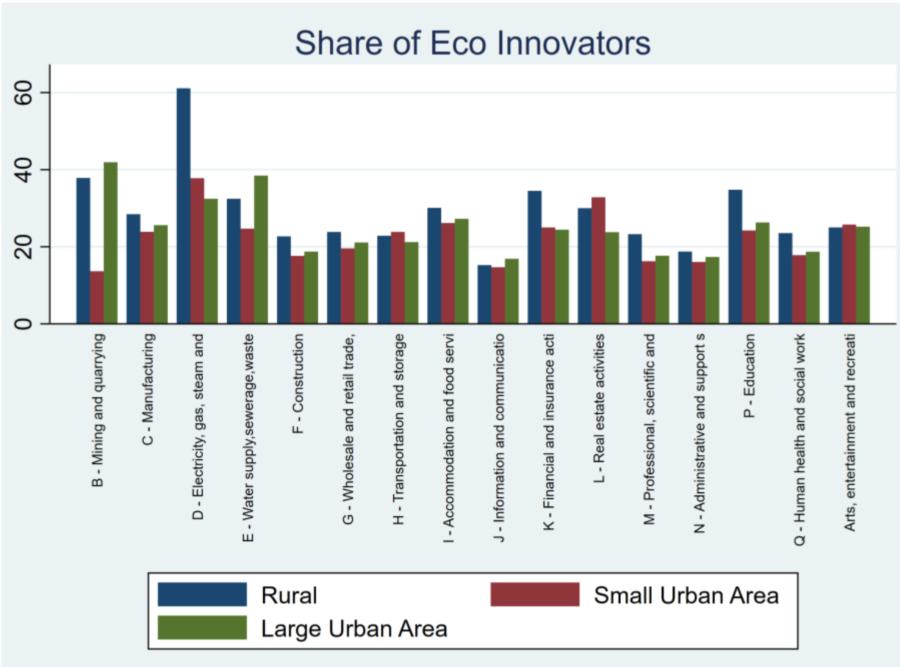

Figure A3

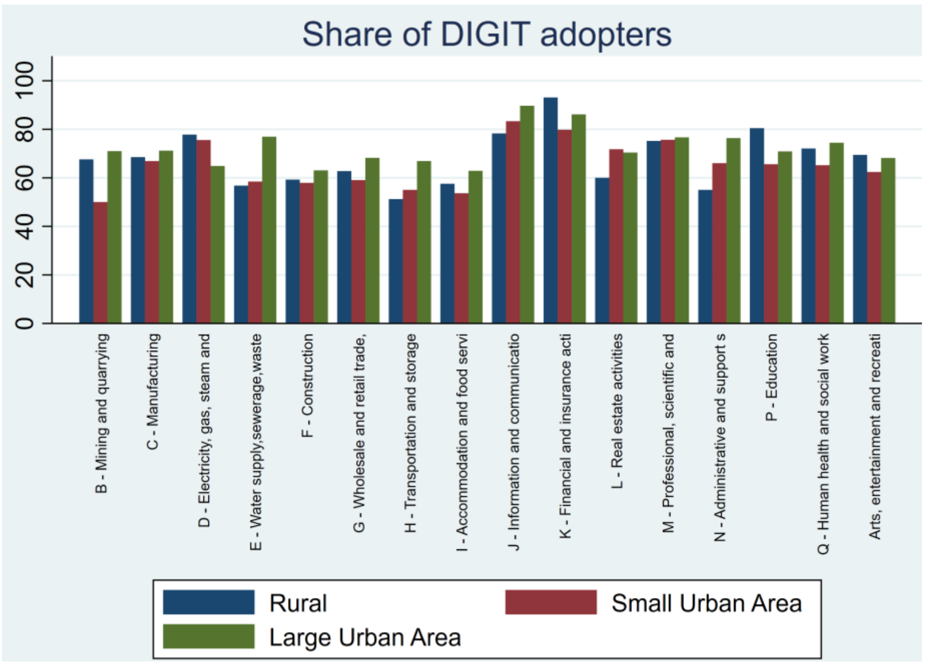

Table 1 – **Descriptive statistics**

Variable	Obs	Mean	Min	Max
EI	14,332	0.22	0	1
DIGIT	14,332	0.67	0	1
Urban Area	14,332	0.85	0	1
Large Urban Area	*14,332*	*0.49*	*0*	*1*
Small Urban Area	*14,332*	*0.36*	*0*	*1*
Rural Area	14,332	0.10	0	1
Green policy support	14,332	0.09	0	1
Border	14,332	0.11	0	1
Industrial	14,332	0.12	0	1
Micro Firm	14,332	0.55	0	1
Small firm	14,332	0.25	0	1
Medium Firm	14,332	0.14	0	1
Large Firm	14,332	0.06	0	1
Exporter	14,332	0.36	0	1
Family business	14,332	0.20	0	1
Patent holder	14,332	0.06	0	1
Firm age (ln)	14,332	2.93	0	6.93
No interest in digitalization	14,332	0.04	0	1

Table 3 – EI and digital technologies by firms in large and small urban areas vs. rural ones

	(a)		(b)		(c)	
	EI	DIGIT	EI	DIGIT	EI	DIGIT
Urban Large	-0.0995***	0.1882***	-0.1516***	0.1835***	-0.2609***	0.1848***
	(0.0369)	(0.0355)	(0.0380)	(0.0356)	(0.0684)	(0.0355)
Urban Small	-0.1317***	0.0666*	-0.1480***	0.0610*	-0.2588***	0.0623*
	(0.0378)	(0.0360)	(0.0380)	(0.0361)	(0.0688)	(0.0360)
DIGIT			0.9181***		0.8007***	
			(0.1687)		(0.1785)	
DIGIT * Urban Large					0.1507*	
					(0.0782)	
DIGIT * Urban Small					0.1555*	
					(0.0801)	
Green policy support	0.2459***		0.2261***		0.2263***	
	(0.0418)		(0.0419)		(0.0419)	
No digital interest		-0.6042***		-0.6504***		-0.6505***
		(0.0575)		(0.0573)		(0.0572)
Controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Country fixed effects	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Industry fixed effects	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Observations	14332		14332		14332	
Chi2	3086		3807		3816	
Rho	0.2542***		-0.3059***		-0.3121***	

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors in parentheses.

Appendix on-line

Appendix A - Descriptive statistics

Table A1 shows some descriptive statistics for the dependent variable (*EI*) and the focal regressor (*Digit*) broken down by our three types of location: large urban area, small urban area and rural area (Columns 1-4). For the sake of comparison, the table also reports the same statistics for technological innovations (product and/or process) in the absence of an environmental impact (Non-EI). Column 5 of the same table displays significance levels of the t-test for differences in means across these localisations.

Table A1 – Cross-location variance of main variables of interest

	(1) Large Urban	(2) Small Urban	(3) Rural	(4) Total	(5) T-test
Digital adopters	70.02	63.49	61.02	66.95	***
Eco-innovators	21.56	21.66	27.35	22.39	***
Non-EI technological innovation	24.33	22.76	20.96	23.38	**

Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The majority (about 67%) of firms included in the sample reportedly adopted at least one of the above-mentioned digital technologies. As expected, and consistently with previous evidence (Holl and Rama, 2021), the share of digital adopters is the lowest (highest) in rural areas (large urban areas), where it remains remarkable (about 61%) but at an appreciable distance from large urban ones (about 71%). Conversely, the share of eco-innovative firms is quite contained overall (about 22%) and shows an opposite distribution across areas: it is the highest (lowest) in rural (small urban) ones, where it reaches a value of about 27%. This is an interesting bit of evidence, which supports the relevance of rural areas for the sustainability outcomes of their firms, which we have recalled in Section 2.

Let us notice that the share of firms that introduce product and/or process innovations in the absence of "environmental benefits" (e.g., non-EI) is significantly higher among urban firms. This is in contrast with respect to firms' eco-innovations, which are significantly more numerous in rural areas.

A first insight about the relationship we are investigating is provided by Figure A1, which shows the share of eco-innovating firms in rural vs. urban (large and small) areas, by discriminating between digital adopters and non-adopters.

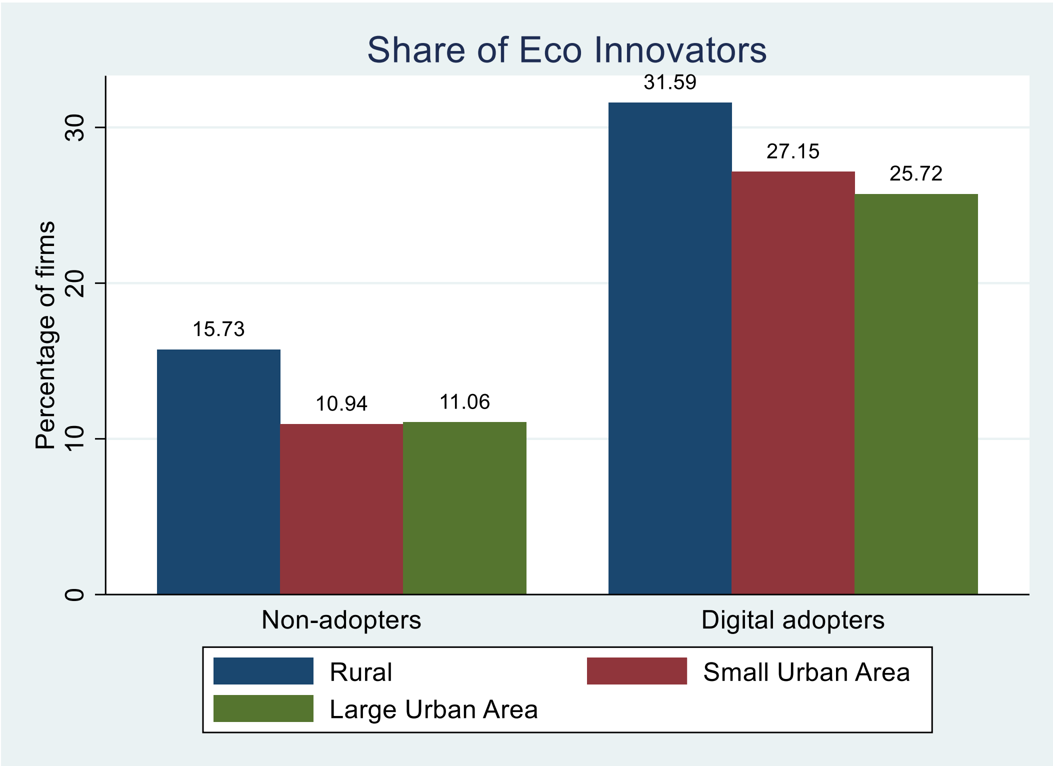

Figure A1 - Share (%) of eco-innovative firms in rural and urban areas

In large urban areas, the share of eco-innovative firms among digital adopters is more than double compared to the same share among non-adopters (25.77% vs 11.04%). In small urban areas, the same share is almost three times higher in the former than in the latter (27.05% vs 10.81%). Conversely, the same gap is relatively lower in rural areas (33.17% vs 17.17%), thus providing preliminary evidence of how localization in urban areas could positively moderate the eco-innovative potential brought about by digital technologies.

Figure 1 (taken from the main text) shows the distribution of the incidence of rural on urban firms across the retained countries, from which a high degree of heterogeneity across European countries emerges.

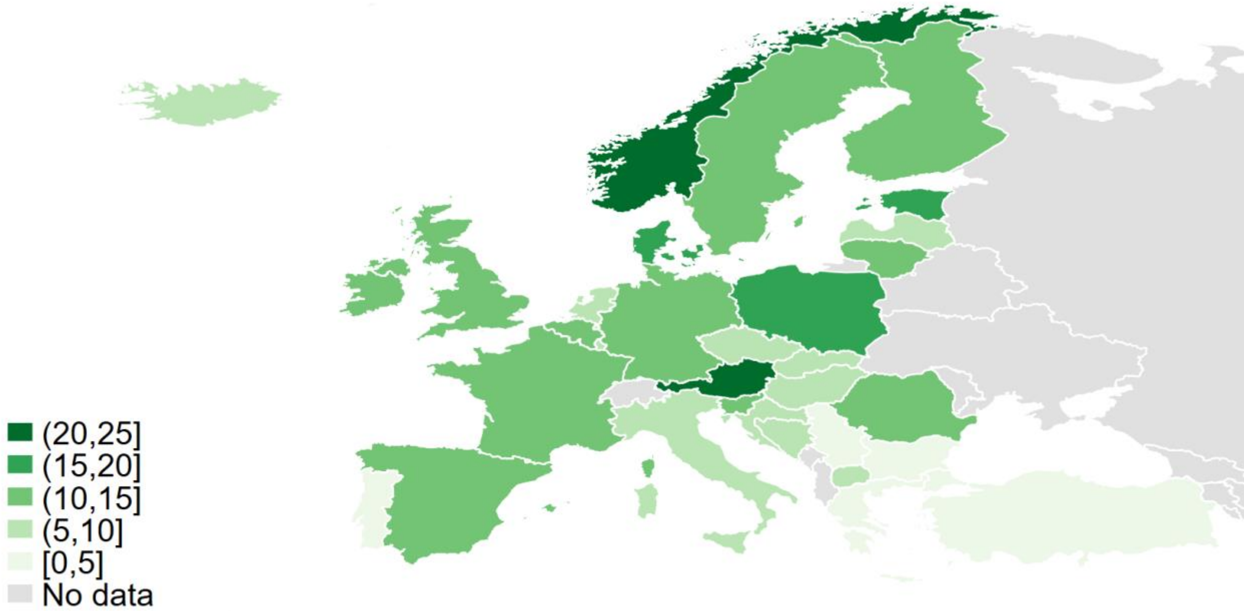

Figure 1 – Shares (%) of rural-based firms across European countries

While on average the incidence of firms based in (declared and perceived) rural areas is about 10%, this is much higher Norway and Austria, followed by Denmark, Estonia and Poland. Italy, Portugal, Greece and Eastern countries show instead a very low incidence of firms based in rural areas.

Interestingly, the large differences in the shares of rural firms at the country level are not associated to differences in the introduction of EI or the adoption of I4.0 technologies,[8] which makes the analysis of the relationships at stake particularly relevant from the micro perspective.

Figure A2 shows the share of firms adopting eco-innovations by sector of economic activity, further differentiating between those which are based in rural versus large and small urban areas. Unfortunately, the Eurobarometer at stake provides the sectoral classification of the sample firms only at the first digit (i.e., single capital letters) of the NACE classification. However, interesting evidence emerges also at this aggregated level of analysis. Apart from arts, entertainment and recreation (R), the share of eco-innovative firms varies in an appreciable way across the retained kinds of locations in every sector. Eco-innovative rural firms are more numerous than their counterparts in urban areas (large and small, in progressive order) across the great majority of the sectors, including in manufacturing, suggesting that the advantages that rural areas can provide to firms in the green realm extend also to production and transformation processes and are not limited

[8] We do not find a statistically significant correlation (neither at the 10% level) between the country share of rural firms and the country shares of firms with EI and DIGITT.

to the supply of services.[9] In general, the gap in EI shares between rural and urban areas is not that large across sectors, with the notable exception of electricity, gas, steam and air conditioning supply (D), where the incidence of eco-innovative firms in rural areas is more than 0.2 percentage point higher than in (large) urban ones. As expected, the energy sector is the one in which the advantages of natural resources and biodiversity can give to rural firms the greatest eco-innovative advantage.

Figure A3 reports the same sectoral-locational disaggregation than Figure A2 with respect to the share of digital firms (adopting at least one of the I4.0 technologies of the questionnaire). As expected, the weight of digital firms in urban areas is heavier than in rural ones across the majority of the sectors, suggesting that a urban-rural digital divide exists across the board irrespectively from sector-specific ways of producing and service supplying. Among the few exceptions, we notice the case of electricity, gas, steam and air conditioning supply (D), where the share of digital firms is higher in rural than in urban ones, mimicking what we found in terms of eco-innovative firms in Figure A2 and supporting the kinds of twin transition we are looking for also in rural areas.[10]

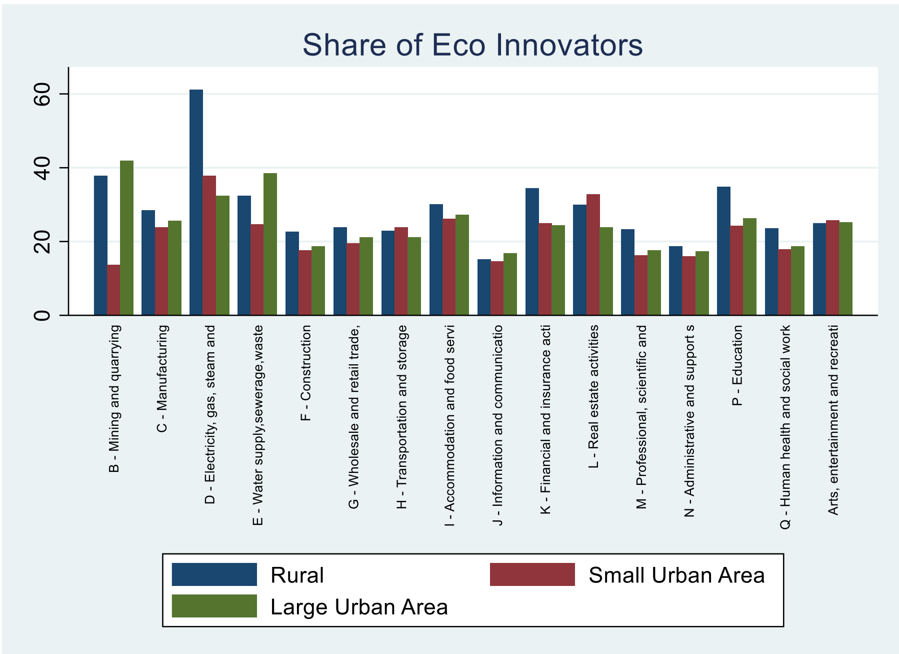

Figure A2 - Share of eco-innovative firms by sector in rural and urban areas

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[9] The only exceptions where eco-innovative urban ones are relatively more numerous than rural ones are mining and quarrying (B), water supply, sewerage, waste management and remediation activities (E), transportation and storage (H), information and communication (J), and real estate activities (L), with the latter two showing a higher share in small than in large areas.

[10] The only other two sectors where digital urban firms are relatively less numerous than digital rural ones are financial and insurance activities (K) and education (P): two sectors in which rural areas might strategically choice to concentrate their digital efforts to contrast their distance (if not even isolation) from urban ones.

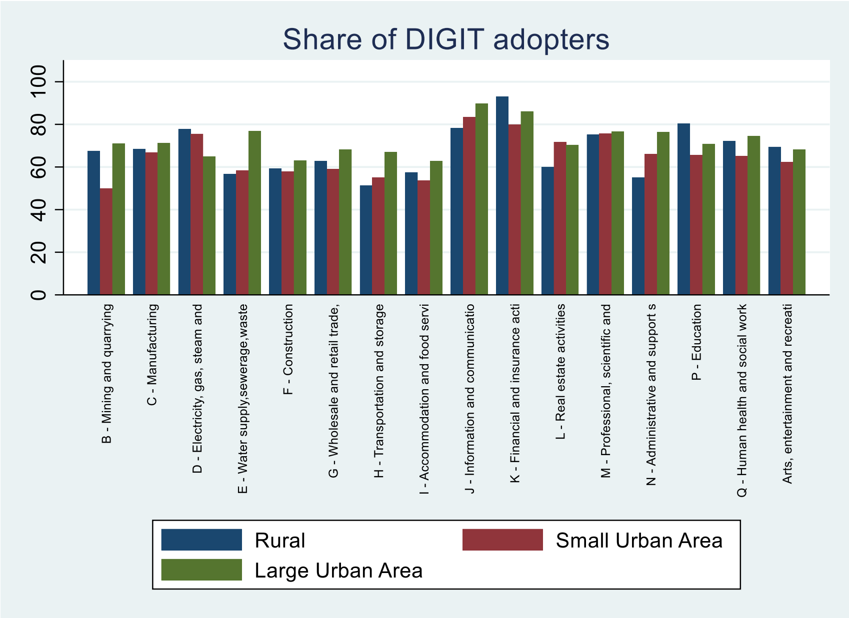

Figure A3 - Share of digital (at least one Industry 4.0 technology) firms, by sector in rural and urban areas

Table A2 shows that the correlations among covariates do not highlight possible collinearity issues.

Table A2 – Correlation Matrix (Tetrachoric correlation coefficients)

ID	Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	EI	1																
2	DIGIT	0.34	1															
3	Urban Area	-0.10	0.04	1														
4	Large Urban Area	-0.03	0.10	1.00	1													
5	Small Urban Area	-0.03	-0.09	1.00	-0.99	1												
6	Rural Area	0.10	-0.09	-0.99	-0.87	-0.76	1											
7	Green policy support	0.14	0.10	-0.02	0.03	-0.04	-0.02	1										
8	border	0.10	0.04	-0.18	-0.23	0.12	0.02	0.01	1									
9	industrial	0.14	0.17	-0.41	-0.18	-0.13	-0.22	0.05	0.16	1								
10	Micro Firm	-0.22	-0.27	0.02	-0.02	0.03	0.07	-0.10	-0.04	-0.18	1							
11	Small firm	0.03	0.09	-0.02	0.00	-0.01	-0.04	0.02	-0.02	0.05	-1.00	1						
12	Medium Firm	0.18	0.25	-0.02	-0.02	0.01	-0.04	0.06	0.06	0.17	-1.00	-1.00	1					
13	Large Firm	0.25	0.26	0.01	0.09	-0.10	-0.07	0.15	0.07	0.11	-1.00	-1.00	-1.00	1				
14	Exporter	0.16	0.25	-0.09	0.00	-0.06	0.01	0.00	0.14	0.22	-0.30	0.08	0.26	0.26	1			
15	Family business	0.20	0.15	-0.10	-0.09	0.04	0.09	0.03	0.08	0.23	-0.04	0.04	0.03	-0.03	0.06	1		
16	Patent holder	0.34	0.34	-0.03	0.04	-0.06	-0.03	0.12	0.12	0.23	-0.28	0.01	0.23	0.31	0.40	0.20	1	
17	No interest in digitalization	-0.22	-0.37	-0.03	-0.01	-0.01	0.04	-0.16	-0.03	-0.06	0.24	-0.13	-0.17	-0.24	-0.17	-0.11	-0.25	1

Table A3 – Shares (%) of firms based in rural areas, introducing EIs by firm size

	(a)	(b)	(c)	(d)	(e)
	Micro firms	Small firms	Medium firms	Large firms	t-test
Rural	11.04%	9.39%	8.92%	8.00%	***
EI	17.69%	23.44%	31.44%	38.93%	***

*Levels of significance for ANOVA TEST in column (e): *** p<0.01, ** p<0.05, * p<0.1*

Appendix B - Robustness checks and additional results

i) Baseline estimates displaying controls

Table B1 – EI and digital technologies by firms in urban vs. rural areas (with full controls)

	(1) Eco-innovator	(2) Eco-innovator	(3) Eco-innovator
Urban	-0.1165***	-0.1526***	-0.2685***
	(0.0345)	(0.0351)	(0.0621)
DIGIT		0.9271***	0.8030***
		(0.1676)	(0.1772)
DIGIT * Urban			0.1611**
			(0.0723)
Boarder area	0.0621	0.0564	0.0553
	(0.0387)	(0.0385)	(0.0385)
Industrial area	0.0216	-0.0160	-0.0143
	(0.0373)	(0.0379)	(0.0378)
Small firm	0.1597***	0.0705*	0.0700*
	(0.0301)	(0.0361)	(0.0360)
Medium firm	0.3637***	0.1958***	0.1939***
	(0.0370)	(0.0534)	(0.0531)
Large firm	0.5600***	0.3711***	0.3698***
	(0.0525)	(0.0687)	(0.0685)
Exporter	0.1679***	0.0703**	0.0690**
	(0.0278)	(0.0351)	(0.0350)
Family businesses	0.1687***	0.1404***	0.1412***
	(0.0305)	(0.0314)	(0.0313)
Patent holder/applicant	0.4343***	0.3518***	0.3518***
	(0.0471)	(0.0512)	(0.0511)
Firm age (ln)	0.0192	0.0314*	0.0314*
	(0.0167)	(0.0168)	(0.0168)
ei_support	0.2379***	0.2344***	0.2348***
	(0.0412)	(0.0412)	(0.0412)
Constant	-1.0055***	-1.5833***	-1.4951***
	(0.1551)	(0.1797)	(0.1842)
Digital Technology Adopter			
Urban	0.1314***	0.1260***	0.1274***
	(0.0333)	(0.0334)	(0.0333)
Boarder area	0.0248	0.0259	0.0260
	(0.0387)	(0.0388)	(0.0387)

Industrial area	0.1546***	0.1441***	0.1439***
	(0.0396)	(0.0397)	(0.0397)
Small firm	0.2813***	0.2789***	0.2789***
	(0.0284)	(0.0284)	(0.0284)
Medium firm	0.5833***	0.5830***	0.5830***
	(0.0391)	(0.0391)	(0.0391)
Large firm	0.6812***	0.6738***	0.6739***
	(0.0614)	(0.0610)	(0.0610)
Exporter	0.3412***	0.3386***	0.3386***
	(0.0271)	(0.0271)	(0.0271)
Family businesses	0.0956***	0.0925***	0.0925***
	(0.0315)	(0.0315)	(0.0315)
Patent holder/applicant	0.3847***	0.3969***	0.3972***
	(0.0597)	(0.0603)	(0.0603)
Firm age (ln)	-0.0372**	-0.0380**	-0.0380**
	(0.0161)	(0.0161)	(0.0161)
No interest in digitalization	-0.6051***	-0.6515***	-0.6515***
	(0.0573)	(0.0570)	(0.0570)
Constant	0.3143**	0.3271**	0.3258**
	(0.1431)	(0.1447)	(0.1447)
/ athrho	0.2546***	-0.3119***	-0.3182***
	(0.0178)	(0.1179)	(0.1169)
Country dummies	Yes	Yes	Yes
Industry dummies	Yes	Yes	Yes
Observations	14332	14332	14332

*Robust standard errors in parentheses; * p < 0.10, ** p < 0.05, *** p < 0.01*

ii) Alternative econometric strategies

Conditional Recursive Mixed Process (C(R)MP)

Using the CRMP, Equations (1) and (2) are estimated simultaneously using the Stata routine cmp, developed by Roodman (2011). This program fundamentally fits a seemingly unrelated regression system (SUR) and estimates parameters that are consistent in case the system itself is “recursive, with clearly defined stages, and that are fully observed, meaning that endogenous variables appear on the right-hand side only as observed”. In this case, the first stage of the seemingly unrelated probit includes an instrument (Digitalisation_interest$_i$) intended to address the endogeneity of

DIGIT. As a consequence, only the final stage displays 'full observability' and the estimation can be described as 'limited-information maximum likelihood'.

In order to better control for the endogeneity of DIGIT, in panel B) of Table B2 below, we also run the CRMP by dropping from the sample the firms belonging to the information and communication sector, whose digitalisation interest if of course driven by their market and less variable than in other ones. Results are still robust.[11]

Table B2 - Conditional Recursive Mixed Process (C(R)MP)

A) All sectors

	(a)		(b)		(c)	
	Eco-innovator	DIGIT	Eco-innovator	DIGIT	Eco-innovator	DIGIT
Urban	-0.1164***	0.1313***	-0.1523***	0.1260***	-0.2683***	0.1249***
	(0.0345)	(0.0333)	(0.0351)	(0.0334)	(0.0622)	(0.0340)
Digital Technology Adopter			0.9139***		0.7903***	
			(0.1694)		(0.1785)	
int_du					0.1614**	
					(0.0724)	
ei_support	0.2461***		0.2262***		0.2265***	
	(0.0418)		(0.0419)		(0.0419)	
No interest in digitalization		-0.6037***		-0.6503***		-0.6415***
		(0.0574)		(0.0571)		(0.0624)
Country dummies	Yes		Yes		Yes	
Controls	Yes		Yes		Yes	
Industry dummies	Yes		Yes		Yes	
Rho	0.2548***		-0.3025**		-0.3093***	
Chi	3078.39		3792.94		3805.84	
Observations	14332		14332		14332	

*Robust standard errors in parentheses; * p < 0.10, ** p < 0.05, *** p < 0.01*

[11] We run an additional robustness check by dropping from the sample firms operating in the Financial and insurance activities (K) as well as those operating in Information and communication (J). The rationale for this further check relies in the fact that sector K displays the highest share of firms adopting I4.0 technologies in the sample, as shown in Fig. A3. Results are robust to this further check and estimates are available upon request.

B) All sectors, excluding sector J - Information and communication

	(a)		(b)		(c)	
	Eco-innovator	DIGIT	Eco-innovator	DIGIT	Eco-innovator	
Urban	-0.1181***	0.1240***	-0.1514***	0.1185***	-0.2747***	0.1176***
	(0.0348)	(0.0334)	(0.0355)	(0.0336)	(0.0626)	(0.0342)
DIGIT			0.8877***		0.7550***	
			(0.1713)		(0.1807)	
DIGIT * Urban					0.1723**	
					(0.0730)	
EI_policy_support	0.2574***		0.2397***		0.2401***	
	(0.0425)		(0.0427)		(0.0426)	
No interest in digitalization		-0.6034***		-0.6488***		-0.6410***
		(0.0581)		(0.0579)		(0.0633)
Country dummies	Yes		Yes		Yes	
Controls	Yes		Yes		Yes	
Industry dummies	Yes		Yes		Yes	
Rho	0.2549***		-0.2852**		-0.2916**	
Chi	2924.75		3614.76		3626.68	
Observations	13771		13771		13771	

*Robust standard errors in parentheses; * p < 0.10, ** p < 0.05, *** p < 0.01*

iii) Baseline estimates with respect to technological EIs

Table B3 – Technological EI and digital technologies by rural-urban firms

	(a)		(b)		(c)	
	EI_Tech	DIGIT	EI_Tech	DIGIT	EI_Tech	DIGIT
Urban	-0.122**	0.130***	-0.153***	0.128***	-0.323***	0.128***
	(0.047)	(0.033)	(0.047)	(0.033)	(0.088)	(0.033)
DIGIT			0.832***		0.660***	
			(0.219)		(0.231)	
DIGIT*Urban					0.226**	
					(0.101)	
EI_policy_support	-0.013		-0.013		-0.012	
	(0.063)		(0.062)		(0.062)	
No_digital_interest		-0.631***		-0.640***		-0.640***
		(0.058)		(0.058)		(0.057)
Controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Industry fixed effects	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Country fixed effects	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant	-2.792***	0.318**	-3.252***	0.323**	-3.122***	0.322**
	(0.393)	(0.144)	(0.396)	(0.144)	(0.399)	(0.144)
Observations	14,332		14,332		14,332	
Chi2	2462		2733		2728	
Rho	0.174**		-0.322**		-0.327***	

*Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1* *iv) Results for the full sample of 40 countries, including Brasil, Canada, Japan and the US*

Table B4 – EI and digital technologies by rural-urban firms (including non-European firms)

	(a)		(b)		(c)	
	EI	DIGIT	EI	DIGIT	EI	DIGIT
Urban	-0.107***	0.139***	-0.145***	0.136***	-0.256***	0.137***
	(0.033)	(0.032)	(0.033)	(0.032)	(0.0595)	(0.031)
DIGIT			0.876***		0.762***	
			(0.165)		(0.172)	
DIGIT*Urban					0.154**	
					(0.069)	
EI_policy_support	0.243***		0.241***		0.241***	
	(0.038)		(0.038)		(0.038)	
No_digital_interest		-0.612***		-0.656***		-0.656***
		(0.055)		(0.055)		(0.055)
Controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Industry fixed effects	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Country fixed effects	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant	-1.007***	0.333***	-1.559***	0.352***	-1.477***	0.351***
	(0.122)	(0.115)	(0.152)	(0.116)	(0.156)	(0.116)
Observations	15,924		15,924		15,924	
Chi2	3387		4084		4100	
Rho	0.250***		-0.268**		-0.276**	

*Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table B5 – Firms' distribution across economic sectors by location (rural vs urban)

	Rural	Urban	Total
B - Mining and quarrying	1.98%	0.38%	0.55%
C - Manufacturing	24.43%	18.17%	18.84%
D - Electricity, gas, steam and air conditioning supply	0.72%	0.59%	0.60%
E - Water supply,sewerage,waste management/remediation activ	1.86%	0.93%	1.03%
F - Construction	9.96%	9.63%	9.67%
G - Wholesale and retail trade, repair of motor vehicles and	25.39%	27.81%	27.55%
H - Transportation and storage	7.02%	5.47%	5.63%
I - Accommodation and food service activities	8.10%	5.50%	5.78%
J - Information and communication	1.56%	4.16%	3.88%
K - Financial and insurance activities	0.96%	2.25%	2.12%
L - Real estate activities	1.68%	2.42%	2.34%
M - Professional, scientific and technical activities	5.22%	10.01%	9.50%
N - Administrative and support service activities	3.54%	4.60%	4.49%
P - Education	2.70%	2.39%	2.42%
Q - Human health and social work activities	3.48%	3.98%	3.92%
Arts, entertainment and recreation	1.38%	1.69%	1.66%
Total	100.00%	100.00%	100.00%

Table B6 – Shares of firms introducing EIs by sector and location (rural vs urban)

	Rural	Urban	Total
B - Mining and quarrying	42.42%	30.19%	34.88%
C - Manufacturing	29.98%	24.69%	25.43%
D - Electricity, gas, steam and air conditioning supply	66.67%	35.37%	39.36%
E - Water supply, sewerage,waste management/remediation activ	35.48%	30.23%	31.25%
F - Construction	19.88%	18.25%	18.43%
G - Wholesale and retail trade, repair of motor vehicles and	24.11%	20.49%	20.85%
H - Transportation and storage	23.08%	22.27%	22.37%
I - Accommodation and food service activities	30.37%	26.70%	27.25%
J - Information and communication	19.23%	16.29%	16.42%
K - Financial and insurance activities	31.25%	24.60%	24.92%
L - Real estate activities	35.71%	27.08%	27.75%
M - Professional, scientific and technical activities	24.14%	17.19%	17.60%
N - Administrative and support service activities	11.86%	16.90%	16.48%
P - Education	35.56%	25.30%	26.53%
Q - Human health and social work activities	24.14%	18.30%	18.85%
Arts, entertainment and recreation	30.43%	25.53%	25.97%
Total	26.59%	21.39%	21.94%