Climate Impact Investing

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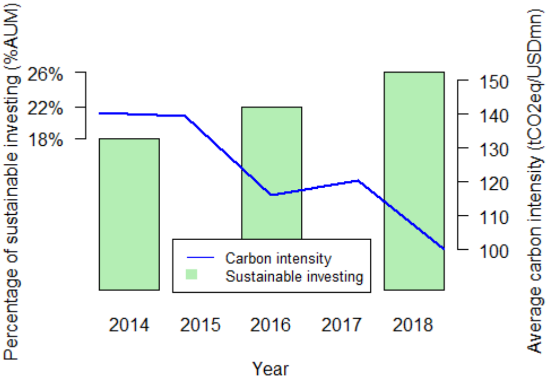
March 9, 2022

Motivation

Does green investing spur companies to reduce their GHG emissions?



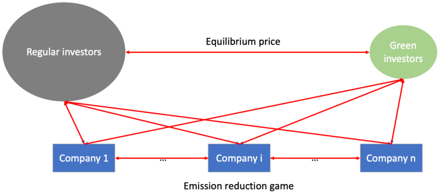
T. De Angelis, P.T. and O. D. Zerbib, Climate Impact Investing. `https://ssrn.com/abstract=3562534`

Related literature on impact investing

- Heinkel, Kraus, and Zechner (2001): When green investors exclude the most polluting companies, they decrease their market value and push them to reform.
- Chowdhry, Davies, and Waters (2018): optimal contracting perspective: impact investors must hold a large enough financial claim to incentivize the company to internalize social externalities.
- Oehmke and Opp (2020): ESG investors relax financial constraint for clean production $\Rightarrow$ trigger the scaling of clean projets; sustainable and regular investors are complementary: together they achieve higher welfare.
- Landier and Lovo (2020): Search frictions in financial markets allow an ESG fund to improve social welfare; the ESG fund forces companies to internalize externalities.
- Pastor et al. (2020): Investors with preferences for ESG issues push (i) all companies (maximizing their market value) to become greener and (ii) green companies to invest more than brown companies.

Outline of the model

- Arbitrage-free complete market with n risky stocks and a risk-free asset, populated by two types of investors, regular and green investors.
- The two types of Investors and the companies have different expectations regarding future cash flows:
- Investors trade in the market maximizing utility of terminal wealth, and determine equilibrium price
- Companies optimize emission schedules to maximize shareholder value $\Rightarrow$ interaction through the price, Nash equilibrium setting



The market

Arbitrage-free complete market with n risky stocks and a risk-free asset ($r = 0$).

Each stock i is a claim on a single liquidating dividend D_T^i at horizon T:

$$D_T = \underbrace{\int_0^T c_t(\psi_t - \psi_b)dt}_{\text{Cost of reform}} + \underbrace{\int_0^T \sigma_t dB_t}_{\text{Cash flow news}},$$

where:

- ψ_t is the emissions vector at time t, ψ_b is the initial emissions; c_t is the marginal abatement cost
- $(B_t)_{t\in[0,T]}$ is a n-dimensional BM on $(\Omega, \mathcal{F}, \mathbb{P})$; σ_t is a deterministic, $n \times n$ invertible matrix $\Rightarrow (\sigma_t dB_t)_{t\in[0,T]}$ is the sequence of cash flow news

Heterogeneous beliefs

The market is populated by two types of investors, regular and green investors.

Investors and companies have different expectations regarding future cash flows:

Heterogeneous beliefs

The market is populated by two types of investors, regular and green investors.

Investors and companies have different expectations regarding future cash flows:

- Under regular investors' probability $\mathbb{P}^r$: reference model
- Under green investors' probability $\mathbb{P}^g$:

$$D_T = \int_0^T c_t(\psi_t - \psi_b)dt + \int_0^T \sigma_t dB_t^g + \int_0^T \theta_s(\psi_s)dt,$$

$$B_t^g = B_t - \int_0^t \sigma_s^{-1}\theta_s(\psi_s)ds$$

  ψ_s: GHG emissions at date s

  $\theta_s(\psi_s) \in \mathbb{R}^n$: financial impacts of climate externalities, $\psi_s \nearrow \Rightarrow \theta(\psi_s) \searrow$

- Under companies's probability $\mathbb{P}^c$:

$$D_T = \int_0^T c_t(\psi_t - \psi_b)dt + \int_0^T \sigma_t dB_t^c + \int_0^T \theta_s^c(\psi_s)dt,$$

Investors' preferences and optimization

Investors maximize expected exponential utility of terminal wealth W_T:

$$\mathbb{E}^j(1 - e^{-\gamma^j W_T^j}), \quad \gamma^j > 0, \quad j \in \{r, g\},$$

Wealth processes follow the dynamics

$$W_t^j = w^j + \int_0^t (N_s^j)^\top dp_s,$$

where N_t^r and N_t^g are quantities of assets held by investors, and prices $(p_t)_{t\in[0,T]}$ are determined by the market clearing.

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We denote by γ^* the global risk aversion, $\frac{1}{\gamma^*} = \frac{1}{\gamma^r} + \frac{1}{\gamma^g}$, and set $\alpha = \frac{\gamma^r}{\gamma^r + \gamma^g}$.

If two investors have the same relative risk aversion at time $t = 0$, $\alpha = \frac{w^g}{w^g + w^r}$ is the proportion of wealth held by green investors at $t = 0$.

Computing the equilibrium price

Assume the equilibrium price has the form

$$dp_t = \mu_t dt + Z_t dB_t$$

Under explonential utility, the investors follow myopic strategies

$$N_t^r = \frac{1}{\gamma^r} M_t^{-1} \mu_t, \qquad N_t^g = \frac{1}{\gamma^g} M_t^{-1} (\mu_t - \theta_t(\psi_t)), \qquad M_t = Z_t^\top Z_t.$$

Market clearing:

$$N_s^r + N_s^g = 1 \quad \Longleftrightarrow \quad \mu_t = \alpha \theta_t(\psi_t)) + \gamma^* M_t 1$$

$\Rightarrow$ the equilibrium price satisfies the quadratic BSDE

$$dp_t = (\alpha \theta_t(\psi_t) + \gamma^* Z_t^\top Z_t 1) dt + Z_t dB_t, \quad p_T = D_T.$$

Equilibrium price and allocation

Proposition

Given a deterministic emissions schedule $(\psi_t)_{t\in[0,T]}$, the unique equilibrium asset price is

$$p_t = D_t - \int_t^T \mu_s ds \quad \text{with} \quad \mu_t = \gamma^* \Sigma_t 1 - \alpha\theta_t(\psi_t)$$

$$\Sigma_t = \sigma_t^\top \sigma_t, \quad D_t = \mathbb{E}[D_T|\mathcal{F}_t].$$

and optimal numbers of shares held by investors in equilibrium are

$$N_t^r = (1-\alpha)\left(1 - \frac{1}{\gamma^g}\Sigma_t^{-1}\theta_t(\psi_t)\right) \quad \text{and} \quad N_t^g = \alpha\left(1 + \frac{1}{\gamma^r}\Sigma_t^{-1}\theta_t(\psi_t)\right),$$

Companies' utility and optimization

At time $t = 0$, company i chooses its emission schedule $(\psi^i_t)_{t\in[0,T]}$ so as to maximize its future market values:

$$\mathcal{J}^i(\psi^i, \psi^{-i}) = \mathbb{E}^c \left[\int_0^T e^{-\rho t} p^i_t(\psi^i, \psi^{-i}) dt \right],$$

where ψ^{-i} are the emission schedules of the other companies and ρ is the rate of time preference.

$\Rightarrow$ Optimal schedule ψ^*: Nash equilibrium, each company determines $\psi^{i,*}$:

$$\mathcal{J}^i(\psi^{*,i}, \psi^{*,-i}) \geq \mathcal{J}^i(\psi^i, \psi^{*,-i}).$$

Equilibrium emissions schedule

Proposition

The optimal emissions schedule maximizes for all $t \in [0, T]$ the quantity

$$c_t^i \psi_t^i + \beta_t^c \theta_t^{i,c}(\psi_t^i) + \alpha \beta_t \theta_t^i(\psi_t^i),$$

where

$$\beta_t^c = \frac{e^{-\rho t} - e^{-\rho T}}{1 - e^{-\rho T}} \underset{\rho \simeq 0}{\simeq} \frac{T - t}{T} \quad \text{and} \quad \beta_t = \frac{1 - e^{-\rho t}}{1 - e^{-\rho T}} \underset{\rho \simeq 0}{\simeq} \frac{t}{T}.$$

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$\Rightarrow$ Trade-off between the cost of reducing the emissions and the positive effect of mitigating the climate-related financial risk perceived by the agents.

Equilibrium emissions schedule

- Special case with quadratic externalities (e.g., quadratic damage function by Barnett, Brock and Hansen, 2019):

Proposition

Assuming $\theta^i_t(x) = \kappa_{0,t} - \frac{\kappa_t}{2}x^2$ and $\theta^c_i(x) = \kappa^c_{0,t} - \frac{\kappa^c_t}{2}x^2$, for $x \geq 0$, where κ_t, κ^c_t, $\kappa_{0,t}$ and $\kappa^c_{0,t}$ are positive deterministic functions of time representing agents' sensitivities to climate externalities, the optimal emissions schedules are

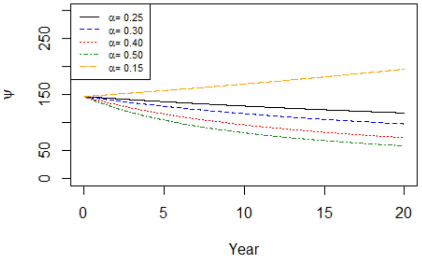
$$\psi^{*,i}_t = \frac{c^i_t}{\beta^c_t \kappa^c_t + \alpha \beta_t \kappa_t}$$

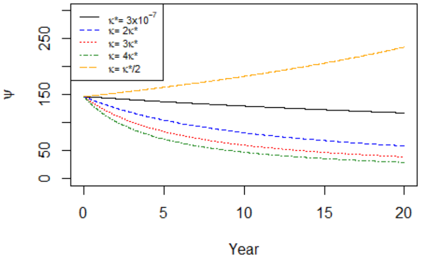
$\rightarrow$ Static interpretation: $\psi^{*,i}_t \searrow$ when $c^i_t \searrow$, and when $\alpha \nearrow$, $\kappa_t \nearrow$, and $\kappa^c_t \nearrow$.

$\rightarrow$ Dynamic interpretation: Long-term emissions are affected by green investors' beliefs (through κ_t, since β_t increases with time) and short-term emissions are affected by companies' beliefs (through κ^c_t, since β^c_t decreases with time).

Equilibrium emissions schedule: simulations

Emissions schedules, according to several values of the proportion of green investors (α, left), and green investors' sensitivity to climate externalities (κ, right).

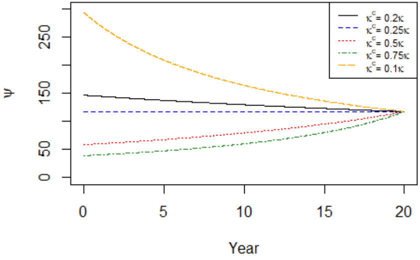


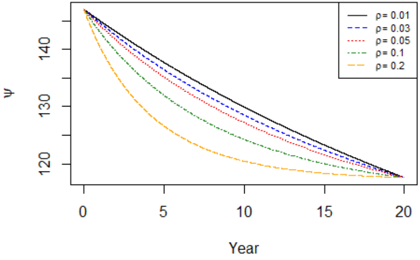


Example: When 25% (50%) of the AUM are managed by green investors, the company reduces its emissions by 1% (3%) per year on average.

Equilibrium emissions schedule: simulations

Emissions schedules, according to several values of companies' sensitivity to climates externalities (κ^c, left), and the rate of time preference (ρ, right).

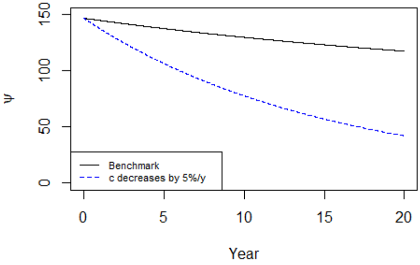




Climate-related technological innovations

$c_t \searrow 5\%$ per year (consistent with Mekaroonreung and Johnson, 2014[1])

$\Rightarrow$ the rate of emissions reduction $\times 3.6$: $\psi_t^* \searrow 3.6\%$ per year on average.



[1] Mekaroonreung and Johnson (2014) estimate the effect of technological change on nitrogen oxides (NOx) marginal abatement costs of U.S. coal power plants in 2000-2008 by analyzing 325 boilers operating in 134 bituminous coal power plants. They find that technological change reduced the NOx marginal cost by 28.3% in 2000-2004 and 26.5% in 2004-2008.

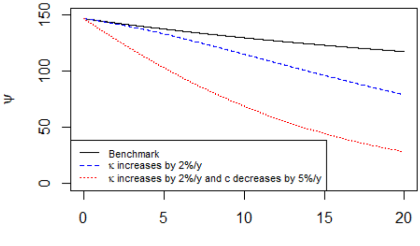
Climate regulation

Case 1, Climate regulation: $\kappa_t \nearrow$ 2% per year (consistent with the required carbon price trajectory to be consistent with the Paris Agreement objectives)

$\Rightarrow$ the rate of emissions reduction $\times 2.2$: $\psi_t^* \searrow$ 2.2% per year on average.

Case 2, Climate regulation + climate-related innovations: $\kappa_t \nearrow$ by 2% per year and $c_t \searrow$ by 5% per year.

$\Rightarrow$ the rate of emissions reduction $\times 4$: $\psi_t^* \searrow$ 4% per year on average.



Strategic interaction effects

The climate risk perceived by the green investors may depend on the general emissions level of the economy as well as on the individual emissions.

Let $\bar{\psi}_t^* = \frac{1}{n}\sum_{j=1}^n \psi_t^{*,j}$ the average optimal emissions of the n companies without interaction effect, and $\varepsilon \geq 0$ an elasticity such that

$$\theta_t^i(\psi) = \kappa_{0,t} - \frac{\kappa_t}{2}\left[(\psi_t^i)^2 + \varepsilon\, \psi_t^i\, \bar{\psi}_t\right] \quad \text{and} \quad \theta_t^{c,i}(\psi) = \kappa_{0,t}^c - \frac{\kappa_t^c}{2}\left[(\psi_t^i)^2 + \varepsilon\, \psi_t^i\, \bar{\psi}_t\right],$$

Then,

$$\psi_t^{*,\varepsilon,i} = \psi_t^{*,i} - \frac{\varepsilon}{2n+\varepsilon}\left(\psi_t^{*,i} + \frac{2n^2}{2n+(n+1)\varepsilon}\bar{\psi}_t^*\right).$$

$$\psi_t^{*,\varepsilon,i} \simeq \psi_t^{*,i} - \frac{\varepsilon}{\varepsilon+2}\bar{\psi}_t^*.$$

<u>Example:</u> $\psi_t^{*,i} = 150$ tCO2/USDmn, $n = 1000$ companies, $\bar{\psi}_t^* = 100$ tCO2/USDmn, $\epsilon = 0.5 \quad \Rightarrow \psi_t^{*,\varepsilon,i} = 130$ tCO2/USDmn

Uncertainty

Fundamental features of climate risks: uncertainty and nonlinearities.

"[...] given historical evidence alone it is likely to be challenging to extrapolate climate impacts on a world scale to ranges in which many economies have yet to experience. Both richer dynamics and alternative nonlinearities may well be essential features of the damages that we experience in the future due to global warming. (Barnett, Brock, Hansen, 2019)"

$\Rightarrow$ we now assume that the relationship between emissions and future dividends, perceived by green investors, is not deterministic, but instead the green investors anticipate future climate shocks occurring at unknown dates

Model with environmental risk: Market and beliefs

The expression for the future dividends under the regular investors' measure remains the same as in the basic model

However, now, green investors internalize *uncertain* future environmental externalities (climate risks) as future random shocks on expected asset pay-offs.

$$D_T = \int_0^T c_t(\psi_t - \psi_b)dt + \int_0^T \sigma_t dB_t + \int_0^T \theta_s(\psi_s)d\mathcal{N}_s^\lambda,$$

where $(\mathcal{N}_t)_{t\in[0,T]}$ is a Poisson process with intensity λ, and $\mathcal{N}_t^\lambda = \lambda^{-1}\mathcal{N}_t$.
$\Rightarrow \mathbb{E}[\mathcal{N}_t^\lambda] = t$ for any λ, i.e., the expected impact of climate shocks is the same as in the basic model
$\Rightarrow$ Generalizes the model with deterministic climate externalities:

$$\lim_{\lambda\to\infty}\int_0^T \theta_s(\psi_s)d\mathcal{N}_s^\lambda = \int_0^T \theta_s(\psi_s)ds.$$

We define similary the dynamics of the terminal dividend under companies' beliefs (probability measure $\mathbb{P}^c$) by replacing $\theta_s(\psi_s)$ by $\theta_s^c(\psi_s)$.

Model with environmental risk: Prices, returns, allocations

Proposition

Given an emission schedule $(\psi_t)_{t\in[0,T]}$, an equilibrium asset price is given by

$$p_t = D_t - \int_t^T \mu_s ds \quad \textit{with} \quad \mu_t = \gamma^* \Sigma_t 1 - \alpha y_\lambda \theta_t(\psi_t),$$

and the optimal number of shares for the regular and green investors are

$$N_t^{r,\lambda} = (1-\alpha)\left(1 - \frac{y_\lambda}{\gamma^g}\Sigma_t^{-1}\theta_t(\psi_t)\right) \quad \textit{and} \quad N_t^{g,\lambda} = \alpha\left(1 + \frac{y_\lambda}{\gamma^r}\Sigma_t^{-1}\theta_t(\psi_t)\right),$$

respectively, where $y_\lambda > 0$ is obtained by solving the one-dimensional equation

$$y_\lambda = \exp\left\{-\frac{\alpha\gamma^g}{\lambda}\left(1^\top \theta_t(\psi_t) + \frac{y_\lambda}{\gamma^r}\theta_t(\psi_t)^\top \Sigma_t^{-1}\theta_t(\psi_t)\right)\right\}. \tag{1}$$

Model with environmental risk: Prices, returns, allocations

Proposition

(i) *Equation* (1) *admits a unique positive solution.*

(ii) *When the level of climate uncertainty increases, green investors choose a less risky portfolio , i.e.,* $\lambda \mapsto (N_t^{g,\lambda})^\top \Sigma_t N_t^{g,\lambda}$ *is increasing in* λ*.*

(iii) *If* $\theta_t(\psi_t)^\top N_t^g > 0$*, then,* $\lambda \mapsto y_\lambda \in [0,1[, \nearrow, \lim\limits_{\lambda\to\infty} y_\lambda = 1$*. Consequently, for a given level of emission schedule,* ψ_t*, the increase in climate uncertainty (*λ *decreases)*

- *pushes green investors to reallocate their wealth towards brown assets;*
- *decreases (increases) the expected returns,* $\mu_t dt$*, of the brown (green) companies.*

(iv) *If* $\theta_t(\psi_t)^\top N_t^g < 0$*, then,* $\lambda \mapsto y_\lambda \in]1,+\infty[, \searrow, \lim\limits_{\lambda\to\infty} y_\lambda = 1$*. Consequently, for a given level of emission schedule,* ψ_t*, the increase in climate uncertainty (*λ *decreases)*

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$\theta_t(\psi_t)^\top N_t^g$:"climate externality" of optimal portfolio of green investors without uncertainty

Model with environmental risk: Prices, returns, allocations

$\theta_t(\psi_t)^\top N_t^g > 0$ is the main case; it occurs when the market is suffciently diversified ("not too brown") or large enough (consistent with Pastor, Stambaugh, and Taylor, 2021; Zerbib, 2020):

Lemma

Fix ψ_t. Assume that the sum of the companies' climate externalities is not too negative, in the sense that $1^\top \theta_t(\psi_t) > -\frac{1}{\gamma^r}\theta_t(\psi_t)^\top \Sigma_t^{-1}\theta_t(\psi_t)$. Then, the green investors' portfolio in the absence of climate uncertainty has positive climate externalities, that is, $\theta_t(\psi_t)^\top N_t^g > 0$.

$\Rightarrow$ For a given ψ_t, climate uncertainty reduces the effect of the externality premium on expected returns, $-\alpha y_\lambda \theta_t(\psi_t)$, which lowers the cost of capital of brown companies and increases the cost of capital of green companies.

Model with environmental risk: Emission schedule

Companies fix their emission schedules at the initial date by maximizing their future market values as in the deterministic case.

Proposition

Let the functions of climate externalities, θ_t^i and $\theta_t^{c,i}$, be defined as in the deterministic case. Assuming that the market is "large enough", an equilibrium emission schedule for the i-th company is

$$\psi_t^{i,*}(y_\lambda^*) = \frac{c_t^i}{\alpha\beta_t\kappa_t y_\lambda^* + \beta_t^c\kappa_t^c},$$

where y_λ^* is a solution of the one-dimensional fixed-point equation

$$y = \exp\left\{-\frac{\alpha\gamma^g}{\lambda}\left[1^\top\theta_t(\psi_t(y)) + \frac{\alpha y}{\gamma^r}\theta_t(\psi_t(y))^\top\Sigma_t^{-1}\theta_t(\psi_t(y))\right]\right\}. \qquad (2)$$

Model with environmental risk: Emission schedule

Proposition

Under the same assumptions as in the previous proposition, the following holds true:

(i) *Existence: For all* $\lambda \in (0, \infty)$*, Equation* (2) *admits at least one positive solution.*

(ii) *Uniqueness: If,* $\forall i \in \{1, \ldots, n\}$*, and* $\forall t \in [0, T]$, $\inf_{y>0} \sum_{j=1}^{n} (\Sigma_t^{-1})_{ij}\, y\, \theta_t^j(\psi_t^j(y)) \geq -\frac{\gamma^r}{\alpha}$*, the solution of Equation* (2) *is unique. Also, in the asymptotic regime where uncertainty is low* ($\lambda \to \infty$)*, the solution is unique.*

$\Rightarrow$ *When this condition is not satisfied and uncertainty is strong, multiple equilibria may exist.*

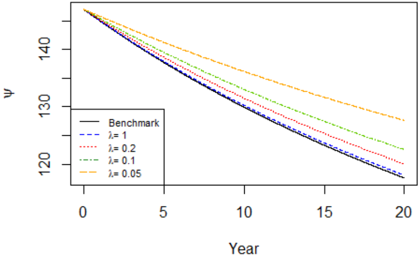
(iii) *Assume that the condition (ii) is satisfied and denote the unique solution by* y_λ^* *and the equilibrium emission schedule without uncertainty by* $\psi_t^{*,0}$*.*

- *If* $\theta_t(\psi_t^{*,0})^\top N_t^g > 0$*, then,* $\lambda \mapsto y_\lambda^* \in [0, 1]$, $\nearrow$, $\lim\limits_{\lambda \to \infty} y_\lambda^* = 1$*. Consequently: an increase in climate uncertainty* ($\lambda \searrow$) $\Rightarrow \psi_t^* \nearrow$
- *If* $\theta_t(\psi_t^{*,0})^\top N_t^g < 0$*, then,* $\lambda \mapsto y_\lambda^* \in]1, +\infty[$, $\searrow$, $\lim\limits_{\lambda \to \infty} y_\lambda^* = 1$*. Consequently: an increase in climate uncertainty* ($\lambda \searrow$) $\Rightarrow \psi_t^* \searrow$

Model with environmental risk: Emission schedule

In the main case described by the lemma above, by mitigating the externality premium on expected returns, green investors reduce the incentive for firms to decrease their emissions at unchanged abatement cost.

⇒ Companies increase their optimal emission schedules in the presence of climate uncertainty by 0.4%, 2%, 4%, and 8.5% when information on climate risks is available every 1, 5, 10, and 20 years.



Empirical illustration

We estimate the following econometric specification:

$$\log(\psi_{i,t+1}) = c + f_i + \beta \log(\tilde{\alpha}_t) + \varepsilon_t^i,$$

where ψ is the CO2 emission intensity of companies and $\tilde{\alpha}_t$ is the proxy for the proportion of green investor wealth, defined by

$$\tilde{\alpha}_t = \frac{\text{Market value of U.S. stocks in green funds holdings at } t}{\text{Total market value of U.S. stocks in } t}$$

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We find that β is negative and highly significant: when the percentage of green assets $\tilde{\alpha}$ doubles, the carbon intensity ψ drops by 5.3% the following year.