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Environmental catching-up, eco-innovation, and technological leadership in China's pilot ecological civilization zones

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A B S T R A C T

In this study we propose a global metafrontier Luenberger productivity indicator (GMLPI) to investigate the effect of the establishment of the Poyang Lake Eco-economic Zone (PLEEZ), one of China's typical ecological civilization zones, on regional environmental total-factor productivity growth. We combine the global environmental technology, metafrontier approach, and the non-radial Luenberger productivity indicator and incorporate the regional heterogeneities into the environmental productivity growth analysis. This GMLPI includes the efficiency change, technological change, and metafrontier technology gap change indices. An empirical study of the PLEEZ has been conducted using the county level data covering a period from 2009 to 2013. Empirical results show that the environmental productivity growth has increased by 8.71% on average, with growth primarily driven by technological change. These results suggest that the establishment of the PLEEZ is effective in encouraging eco-innovation; however the PLEEZ lacks an eco-leadership effect. Significant heterogeneities in environmental productivity growth and its patterns among three major functional zones in the PLEEZ remain.

1. Introduction

The Poyang Lake Eco-economic Zone Planning was officially approved by the State Council of China on December 12th, 2009, indicating that the construction of the Poyang Lake Eco-economic Zone (PLEEZ) was a national-level strategy. The PLEEZ is based on the Poyang lake urban circle and is intended to become an ecological economic demonstration zone and a low-carbon economy development priority zone in China.[1] The increasing interest in and strategic importance of the PLEEZ have heightened the need for investigating its effects on regional environmental performance.

Therefore this study investigates the effect of the PLEEZ's establishment on regional environmental productivity growth after 2009. A significant growth of the environmental productivity of the PLEEZ after 2009 indicates that the PLEEZ policy is effective.

Two kinds of indices are widely used for measuring productivity growth, i.e. the Malmquist index and the Luenberger indicator. The Malmquist index, empirically presented by Färe et al. (1994), is widely used for measuring productivity change growth. Taking the environmental factors into account, Chung et al. (1997) proposed the Malmquist–Luenberger index for measuring environmentally sensitive productivity growth. Empirical studies applying the Malmquist–Luenberger index include Weber and Domazlicky (2001), Färe et al. (2001), Yörük and Zaim (2005), Kumar (2006) and Zhang and Choi (2013a,b), for measuring environmental performance change.

The Luenberger productivity indicator is an alternative for measuring productivity growth. Compared with the Luenberger indicator, the Malmquist index appears to overestimate productivity changes (Boussemart et al., 2003). Recent work also suggests that the Luenberger index is more robust than the Malmquist index (Fujii et al., 2014). Thus, this study employs the Luenberger indicator as its main methodology. However, the basic Luenberger indicator cannot deal with the non-zero slack variable problem because it adopts the radial method for measuring performance (Zhou et al., 2012; Zhang et al., 2014). To handle this shortcoming, Fujii et al. (2014) proposed the non-radial Luenberger indicator with undesirable outputs. To incorporate cross-group heterogeneity into this indicator, Zhang and Wei (2015) introduced a metafrontier non-radial Luenberger carbon emission performance index; unlike Zhang and Wei (2015), who focused on single-factor carbon emission performance change, we propose a metafrontier

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[1] For details about the PLEEZ, please see Appendix A.

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non-radial Luenberger productivity indicator to measure the total-factor environmentally sensitive productivity growth. Compared with the methodologies adopted in existing energy and environmental studies (e.g. Wang et al., 2013, 2015; Zhang and Wei, 2015),[2] the key innovativeness of the proposed approach is that it can handle both non-zero slack variables and cross-group heterogeneity simultaneously. We then use the proposed approach to measure environmental productivity growth and its patterns in the PLEEZ at a county level.

This study has two major contributions to the current literature. Practically, although a number of studies have focused on the environmental productivity growth for China's provinces (Zhang et al., 2011; Choi et al., 2015) or China's industries (Chen and Golley, 2014; Li and Lin, 2015), no studies have explored the PLEEZ, a national-level strategy. This study thus addresses this research gap by evaluating the PLEEZ, thus enabling us to get insight into the effectiveness of this national-level strategy. Methodologically, we develop an integrated methodology called the Global Metafrontier non-radial Luenberger Productivity Indicator (GMLPI) to measure environmental productivity growth. This methodology combines a non-radial directional distance function, Luenberger productivity indicator, and the global metafrontier approach. It can thus incorporate slack variables, undesirable outputs, and group heterogeneities when measuring environmental productivity growth.

The remainder of this paper is organized as follows. Section 2 introduces the methodology used. Section 3 conducts the empirical study. Section 4 concludes this study.

2. Methodology

2.1. Non-radial directional distance function

We assume that there are $j = 1, \ldots, N$ observations, which are different counties in the PLEEZ, and each region uses input vector $x \in \Re_+^M$ to produce good economic output vector $y \in \Re_+^S$ as well as undesirable pollutant vector $b \in \Re_+^J$. Thus, the environmental production technology can be expressed as follows:

$$T = \{(x, y, b) : x \text{ can produce } (y, b)\}, \tag{1}$$

where T is the environmental production technology. We assume that it satisfies the standard axioms of production theory (Färe and Grosskopf, 2005). That is, finite amounts of inputs can produce only finite outputs. Inputs and desirable outputs are often assumed to be freely (strong) disposable. For modeling joint-production technologies (Färe et al., 1989) with undesirable outputs, weak disposability and null-jointness assumptions should be imposed on the environmental production technology T, as follows:

(i) If $(x,y,b) \in T$ and $0 \le \theta \le 1$, then $(x,\theta y,\theta b) \in T$;
(ii) If $(x,y,b) \in T$ and $b = 0$, then $y = 0$.

The weak-disposability assumption implies that pollutant abatement activities are costly in terms of proportional reductions in product output. Meanwhile, the null-jointness assumption indicates that the pollutants are not avoidable in the PLEEZ unless economic activities are stopped.

Following the literature, a piecewise non-parametric linear frontier is adopted to construct the environmental production technology. The environmental technology T for N observations with constant returns to scale may then be expressed as follows:

$$\begin{aligned} T = \{(x, y, b) \quad : & \sum_{n=1}^{N} z_n x_{mn} \le x_m, m = 1, \ldots, M, \\ & \sum_{n=1}^{N} z_n y_{sn} \ge y_s, s = 1, \ldots, S, \\ & \sum_{n=1}^{N} z_n b_{jn} = b_j, j = 1, \ldots, J, \\ & z_n \ge 0, n = 1, \cdots, N\}. \end{aligned} \tag{2}$$

where M, S and J denote the number of inputs, desirable outputs and undesirable outputs, respectively.

After defining the environmental technology, the non-radial directional distance function (DDF) is followed. The formal definition of the non-radial DDF was first introduced by Zhou et al. (2012). Compared with other energy and environmental modeling techniques, a unique advantage of DDF is its capability of expanding desirable outputs and lessening inputs or undesirable outputs simultaneously. A review of DDF application in energy and environmental studies can be found in Zhang and Choi (2014). Following Zhou et al. (2012), the non-radial DDF with undesirable output is defined as:

$$\vec{D}(x, y, b; g) = \sup\{\mathbf{w}^T \boldsymbol{\beta} : ((x, y, b) + g \cdot diag(\boldsymbol{\beta})) \in T\}. \tag{3}$$

where $\mathbf{w} = (w_m^x, w_s^y, w_j^b)^T$ denotes a normalized weight vector corresponding to the number of inputs and outputs, $g = (-g_x, g_y, -g_b)$ is an explicit directional vector, and $\beta = (\beta_m^x, \beta_s^y, \beta_j^b)^T \ge 0$ denotes the scaling factors indicating the inefficiencies. Thus the value of $\vec{D}(x, y, b; g)$ under the environmental technology can be calculated by solving the following DEA-type model:

$$\begin{aligned} \vec{D}(x, y, b; g) = & \max\left(w_m^x \beta_m^x + w_s^y \beta_s^y + w_j^b \beta_j^b\right) \\ \text{s.t.} & \sum_{n=1}^{N} z_n x_{mn} \le x_m - \beta_m^x g_{xm}, m = 1, \ldots, M, \\ & \sum_{n=1}^{N} z_n y_{sn} \ge y_s + \beta_s^y g_{ys}, s = 1, \ldots S, \\ & \sum_{n=1}^{N} z_n b_{jn} = b_j - \beta_j^b g_{bj}, j = 1, \ldots J, \\ & z_n \ge 0, n = 1, 2, \cdots, N \\ & \beta_m^x, \ \beta_s^y, \beta_j^b \ge 0. \end{aligned} \tag{4}$$

The directional vector g can be set up in different ways, based on given policy goals. If $\vec{D}(x, y, b; g) = 0$, then the specific unit to be evaluated is located on the frontier of the best practices in the direction of g.

2.2. Global metafrontier Luenberger productivity indicator (GMLPI)

Following Zhang and Choi (2013a,b) and Zhang and Wei (2015), three environmental technologies: contemporaneous, intertemporal, and global environmental technologies are needed to define the GMLPI and its decompositions.

The contemporaneous environmental technology for group R_h at time t is defined as $T_{R_h}{}^c = \{(x^t, y^t, b^t) : (x^t) \text{ can produce } (y^t, b^t)\}$, where $t = 1, \ldots, T$. The intertemporal environmental production technology of group R_h is defined as $T_{R_h}{}^I = T_{R_h}{}^1 \cup T_{R_h}{}^2 \cup \ldots \cup T_{R_h}{}^T$. The intertemporal environmental technology can be interpreted as the single technology set that encompasses all contemporaneous environmental technologies from whole period only for the specific group R_h. The global environmental production technology is defined as $T^G = T_{R_1}{}^I \cup T_{R_2}{}^I \cup \ldots \cup T_{R_H}{}^I$, which is constructed from all observations over the whole period for all groups. This implies that the global environmental technology encompasses all intertemporal environmental production technologies,

[2] For a comprehensive review please see Zhang and Choi (2014).

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Table 1
Descriptive statistics.

Variable		Unit	Mean	St. dev.	Min	Max
GDP	Good output	10^8 Yuan	159.1	133.5	20.5	814.9
Waste water	Bad output	10^4 ton	2774.5	2993.9	280.8	25,921.7
SO_2	Bad output	ton	8994.3	13,270.7	41.2	58,524.1
Soot	Bad output	ton	3570.5	8091.3	20.3	94,012.8
Capital	Input	10^8 Yuan	570.6	413.7	54.2	2516.6
Labor	Input	10^4	27.7	19.4	3.8	94.0
Energy	Input	10^4 ton	75.3	124.4	0.1	671.7

and it is assumed that all observations can access the global technology through their eco-innovation.

The contemporaneous non-radial DDF is constructed based on the contemporaneous environmental production technology ($T_{R_h}{}^c$) of specific group R_h. Similarly, the intertemporal non-radial DDF is defined as $\vec{D}^I(.) = \sup\{\mathbf{w}^T\boldsymbol{\beta}^I : ((x,y,b)+g\cdot diag(\boldsymbol{\beta}^I))\in T^I_{R_h}\}$ based on the intertemporal environmental production technology ($T_{R_h}{}^I$) of group R_h. Finally the global DDF: $\vec{D}^G(.) = \sup\{\mathbf{w}^T\boldsymbol{\beta}^G : ((x,y,b)+g\cdot diag(\boldsymbol{\beta}^G))\in T^G\}$ is based on the global environmental production technology (T^G).

To calculate and decompose the GMLPI, we need to solve six different functions: $\vec{D}^C(x^s,y^s,b^s)$, $\vec{D}^I(x^s,y^s,b^s)$, and $\vec{D}^G(x^s,y^s,b^s)$, $S = t$, $t+1$. The NDDFs can be computed by using the following DEA-type models:

$$\begin{aligned}\vec{D}^d(x^s,y^s,b^s;g) = \max w_x\beta_x^d + w_y\beta_y^d + w_b\beta_b^d \\ \text{s.t.} \sum_{con} z_n^s x_n^s \le x_{n'} - \beta_x^d g_x \\ \sum_{con} z_n^s y_n^s \ge y_{n'} + \beta_y^d g_y \\ \sum_{con} z_n^s b_n^s = b_{n'} - \beta_b^d g_b \\ z_n^s \ge 0, \beta^d \ge 0\end{aligned} \quad (5)$$

Here the superscript d on $\vec{D}^d(x^s,y^s,b^s;g)$ represents the different type of NDDF, which can be contemporaneous, intertemporal, or global. The symbol *con* under $\sum$ represents the conditions for constructing the three environmental production technologies. The contemporaneous NDDF should follow the conditions d ≡ C and con ≡ $\{n\in R_h\}$; the intertemporal NDDF, d ≡ I and con ≡ $\{n\in R_h, s\in[1,2,\ldots,T]\}$; and for the global NDDF, d ≡ G and con ≡ $\{n\in[R_1 \cup R_2 \cup \ldots \cup R_H], s\in[1,2,\ldots,T]\}$.

Following the idea of the Luenberger indicator which is based on the DDF, the GMLPI is defined as follows

$$GMLPI\left(x^S,y^S,b^S\right) = \vec{D}^G\left(x^{t+1},y^{t+1},b^{t+1}\right) - \vec{D}^G\left(x^t,y^t,b^t\right) \quad (6)$$

The GMLPI in Eq. (6) measures the environmental productivity growth using an additive measure based on the differences between

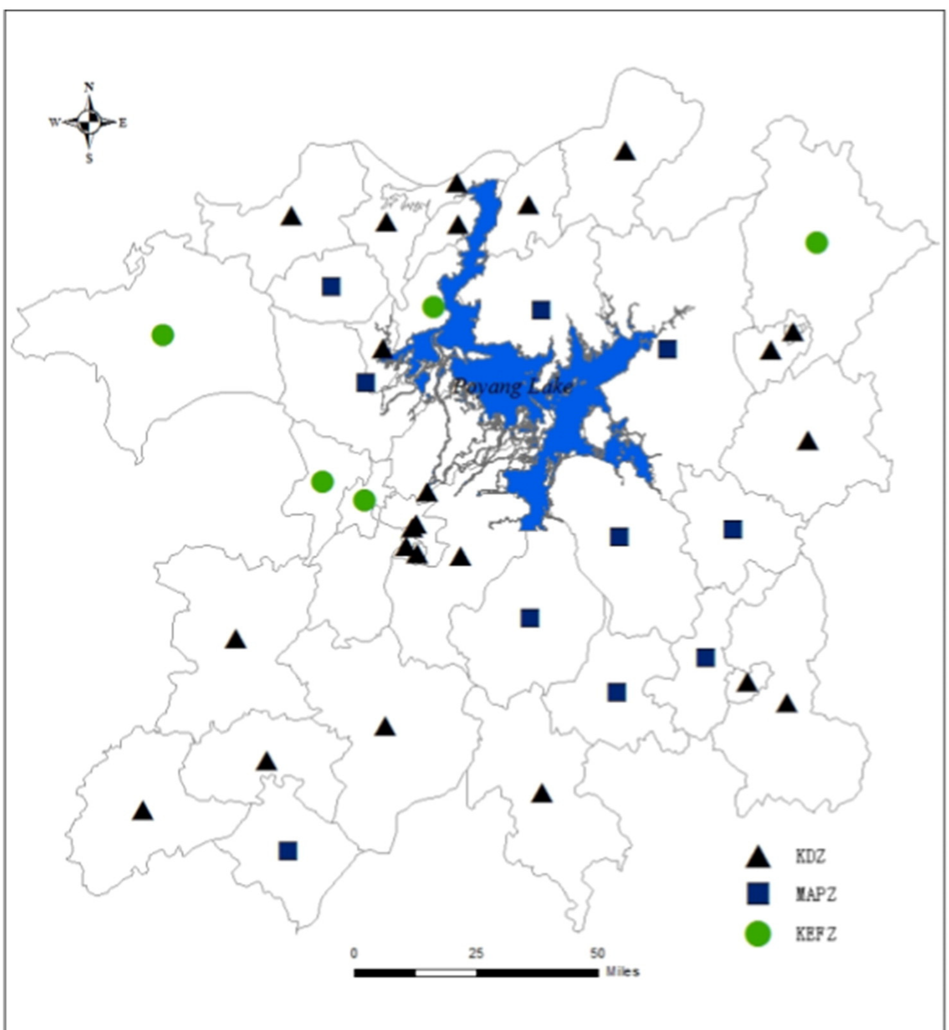

Fig. 1. Illustration of Major functional Zones in the PLEEZ.

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Table 2
Basic statistics for three major functional zones.

Group	GDP (10^8 Yuan)		Energy (10^4 ton)		Capital (10^8 Yuan)		Labor (10^4)		SO2 (ton)	
	Mean	Growth	Mean	Growth	Mean	Growth	Mean	Growth	Mean	Growth
KDZ	214.3167	14.78%	111.7367	3.90%	706.2642	16.72%	28.58847	4.77%	13,120.09	3.72%
MAPZ	84.94987	16.60%	26.8112	1.04%	380.2558	9.88%	33.07815	0.68%	3241.925	6.40%
KEPZ	53.5446	15.68%	4.4205	4.61%	327.0234	7.37%	12.77227	1.74%	1520.433	3.43%
PLEEZ	117.6037	15.69%	47.65614	3.18%	471.1811	11.33%	24.81296	2.40%	5960.818	4.52%

two DDFs. From Eq. (6), the GMLPI measures the observation of movement (toward or away from) of the global environmental production possibilities frontier from period t to $t+1$. GMLPI > 0 indicates that the environmental productivity growth has been improved, and then the observation is moving toward the global environmental frontier. If GMLPI = 0, the productivity does not change. If GMLPI < 0, the environmental productivity drops and the observation is moving away from the global frontier.

The GMLPI can be decomposed into a group technical efficiency change (EC) index, a group technological change (TC) index, and a metafroniter technology gap change (MGC) index of environmental productivity. The decomposition process is as follows:

$$\begin{aligned}
GMLPI\left(x^S,y^S,b^S\right) &= \vec{D}^G\left(x^{t+1},y^{t+1},b^{t+1}\right)-\vec{D}^G\left(x^t,y^t,b^t\right)\\
&=\left[\vec{D}^{t+1}\left(x^{t+1},y^{t+1},b^{t+1}\right)-\left[\vec{D}^t\left(x^t,y^t,b^t\right)\right]\right.\\
&\quad+\left\{\left[\vec{D}^I\left(x^{t+1},y^{t+1},b^{t+1}\right)-\vec{D}^{t+1}\left(x^{t+1},y^{t+1},b^{t+1}\right)\right]\right.\\
&\quad\left.-\left[\vec{D}^I\left(x^t,y^t,b^t\right)-\vec{D}^t\left(x^t,y^t,b^t\right)\right]\right\}\\
&\quad+\left\{\left[\vec{D}^G\left(x^{t+1},y^{t+1},b^{t+1}\right)-\vec{D}^I\left(x^{t+1},y^{t+1},b^{t+1}\right)\right]\right.\\
&\quad\left.-\left[\vec{D}^G\left(x^t,y^t,b^t\right)-\vec{D}^I\left(x^t,y^t,b^t\right)\right]\right\}\\
&=\left(TE^{t+1}-TE^t\right)+\left(TC^{t+1}-TC^t\right)+\left(MGC^{t+1}-MGC^t\right)\\
&=EC+TC+MGC
\end{aligned} \tag{7}$$

The efficiency change (EC) index in Eq. (7) measures the "catch-up" effect in terms of technical efficiency changes in environmental productivity for a specific observation in a group during two periods $(t, t+1)$. EC captures how close an observation is moving toward the contemporaneous environmental production possibilities frontier. Here EC > (or <) 0 means an efficiency gain (or loss).

The technological change (TC) index measures changes in the best-practice gap for the environmental technology between the contemporaneous environmental technology and the intertemporal environmental technology during two periods. TC > (or <) 0 means that the contemporaneous technology frontier shifts toward (or away from) the intertemporal technology frontier. Because TC measures frontier shifts in a contemporaneous technology, it can be considered to be a measure of eco-innovation effect.

Metafrontier gap change (MGC) is a measure of changes in the metafrontier technology gap (MTG) for eco-frontier shift between the intertemporal environmental production technology frontier and the global frontier during two periods. TGC > (or <) 0 indicates a decrease (or increase) in the meta-technology gap between the intertemporal technology for a specific group and the global environmental technology. Therefore, MGC represents the eco-technological leadership change for a given group.

3. Empirical analysis

3.1. Data

The GMLPI explained in Section 2 is used to measure environmental productivity growth and its patterns in the 38 counties in the PLEEZ during the period from 2009 to 2013. First, we describe how the data for the empirical study was collected.

For the output variables, because our study focuses on regional environmental economies, we choose regional real GDP to represent the only desirable output. For the input variables, we choose labor, capital and energy consumption data. We use the number of employed labor force as the labor data. Because the capital stock data is unavailable, we use the growth rate approach to estimate the capital stock for each county. The growth rate approach has been proved to be an effective one in Young (2003).

Based on this approach, the capital stock can be calculated as:

$$K_{n,t}=\frac{\Delta K_{n,t+1}}{(\delta_n+g_n)} \tag{8}$$

where $K_{n,t}$ denotes the capital stock of region n in time t, $\Delta K_{n,t+1}$ is the investment in capital of region n in time $t+1$, and δ_n and g_n indicate the depreciation rate and GDP growth rate of region n, respectively. The data of δ_n for Jiangxi Province comes from Wu (2009).

Table 3
Changes in the GMLPI in the 38 PLEEZ regions, 2009–2013.

Regions	Groups	09–10	10–11	11–12	12–13	Mean
Changjiang District	KDZ	−0.0321	0.0844	0.0313	−0.1287	−0.0113
Donghu District	KDZ	0.1289	0.4756	0.5794	0.5665	0.4376
Fengcheng City	KDZ	0.1651	−0.1665	0.0369	0.0027	0.0096
Gaoan City	KDZ	0.1779	−0.1561	0.0241	0.0029	0.0122
Gongqincheng City	KDZ	0.2365	0.2665	0.0407	0.3773	0.2302
Guixi City	KDZ	0.052	0.0335	0.1033	0.0712	0.065
Hukou County	KDZ	−0.0567	0.0402	−0.0011	0.0326	0.0037
Jiujiang County	KDZ	0.2161	−0.222	0.0134	−0.005	0.0006
Leping City	KDZ	0.0944	0.0447	0.0313	0.0339	0.0511
Linchuan District	KDZ	0.1216	−0.0497	0.0347	0.0376	0.036
Lushan District	KDZ	0.0074	0.0303	−0.0664	0.0236	−0.0013
Nanchang County	KDZ	0.4824	0.9346	0.0673	0.2994	0.4459
Pengze County	KDZ	0.0719	−0.2907	0.0128	−0.0354	−0.0604
Qingshanhu District	KDZ	−0.1203	0.0304	−0.0675	−0.0195	−0.0442
Qingyunpu District	KDZ	−0.0876	0.3561	−0.023	0.0624	0.077
Ruichang City	KDZ	0.0263	0.0177	0.0198	−0.0262	0.0094
Xihu District	KDZ	0.1284	0.6217	0.4899	0.5858	0.4565
Xinjian County	KDZ	0.1035	0.2447	0.0468	0.1279	0.1307
Xunyang District	KDZ	0.305	0.248	0.0654	0.1558	0.1935
Yushui District	KDZ	0.1301	−0.0368	−0.0251	0.0727	0.0352
Yuehu District	KDZ	0.1114	0.7385	0.1531	0.1672	0.2926
Zhangshu City	KDZ	0.1418	−0.2544	0.0692	−0.0223	−0.0164
Zhushan District	KDZ	0.151	0.1819	0.3417	0.2329	0.2269
Dean County	MAPZ	0.2592	0.0717	0.1484	0.1521	0.1578
Dongshan County	MAPZ	0.1841	0.0532	0.0984	0.1316	0.1168
Duchang County	MAPZ	0.0496	−0.1909	0.0344	0.0039	−0.0257
Jinxian County	MAPZ	0.1528	0.2462	0.0989	0.0446	0.1356
Poyang County	MAPZ	0.1015	−0.1046	0.0249	−0.0228	−0.0002
Wannian County	MAPZ	−0.1184	0.2891	0.2998	0.1307	0.1503
Xingan County	MAPZ	0.1648	−0.1334	0.0764	0.0074	0.0288
Yongxiu County	MAPZ	0.0672	−0.1189	0.1854	−0.0282	0.0264
Yugan County	MAPZ	0.3548	−0.2645	0.0992	−0.0337	0.0389
Yujiang County	MAPZ	0.3646	0.0349	−0.0191	−0.0147	0.0914
Anyi County	KEFZ	0.0799	0.0372	0.0128	0.0369	0.0417
Fuliang County	KEFZ	0.0385	0.0201	−0.0707	0.0102	−0.0005
Wanli District	KEFZ	0.0244	0.1595	−0.1003	0.0015	0.0212
Wuning County	KEFZ	0.2181	−0.2689	0.017	−0.0075	−0.0103
Xingzi County	KEFZ	−0.3823	0.1517	0.1315	−0.0774	−0.0441
Mean	PLEEZ	0.1083	0.083	0.0793	0.0776	0.0871

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Table 4
Group efficiency change component of the GMLPI, 2009–2013.

Regions	Group	09–10	10–11	11–12	12–13	Mean
Changjiang District	KDZ	−0.0923	−0.2270	0.0121	−0.2074	−0.1286
Donghu District	KDZ	0.0000	0.0000	0.0000	0.0000	0.0000
Fengcheng City	KDZ	−0.0311	−0.4497	0.0374	−0.0658	−0.1273
Gaoan City	KDZ	0.0880	−0.2899	0.0130	−0.0805	−0.0674
Gongqincheng City	KDZ	0.0000	0.0000	0.0000	0.0000	0.0000
Guixi City	KDZ	−0.0242	−0.0263	0.0193	−0.0292	−0.0151
Hukou County	KDZ	−0.1293	−0.0384	−0.0028	0.0233	−0.0368
Jiujiang County	KDZ	0.0000	−0.2827	−0.0789	−0.0798	−0.1103
Leping City	KDZ	−0.0106	−0.0591	0.0068	−0.0308	−0.0234
Linchuan District	KDZ	0.0530	−0.1901	0.0180	−0.0059	−0.0312
Lushan District	KDZ	−0.1146	−0.1168	−0.0803	−0.0012	−0.0782
Nanchang County	KDZ	0.3302	0.0000	0.0000	0.0000	0.0825
Pengze County	KDZ	−0.1266	−0.3513	−0.0239	−0.0606	−0.1406
Qingshanhu District	KDZ	−0.1667	−0.0022	−0.0675	−0.0212	−0.0644
Qingyunpu District	KDZ	−0.1339	0.0891	−0.0554	0.0007	−0.0249
Ruichang City	KDZ	−0.0799	−0.0959	−0.0371	−0.0797	−0.0731
Xihu District	KDZ	0.0000	0.0000	0.0000	0.0000	0.0000
Xinjian County	KDZ	−0.0551	0.1064	0.0089	−0.0121	0.0120
Xunyang District	KDZ	0.0000	0.0000	0.0000	0.0000	0.0000
Yushui District	KDZ	0.0000	−0.1211	−0.0995	0.0230	−0.0494
Yuehu District	KDZ	0.0674	0.0006	0.0000	0.0000	0.0170
Zhangshu City	KDZ	0.0000	−0.2699	0.0123	−0.0816	−0.0848
Zhushan District	KDZ	0.0000	0.0000	0.0000	0.0000	0.0000
Dean County	MAPZ	0.0041	0.0000	0.0000	0.0000	0.0010
Dongshan County	MAPZ	0.0282	0.0704	0.1479	0.1634	0.1025
Duchang County	MAPZ	−0.1189	−0.0578	−0.1260	0.0994	−0.0508
Jinxian County	MAPZ	0.0000	0.0000	0.0000	0.0000	0.0000
Poyang County	MAPZ	0.0000	0.0000	0.0000	0.0000	0.0000
Wannian County	MAPZ	−0.0906	0.0906	0.0000	0.0000	0.0000
Xingan County	MAPZ	−0.0087	−0.1305	−0.0219	−0.0451	−0.0516
Yongxiu County	MAPZ	−0.0167	−0.0454	0.0414	−0.0353	−0.0140
Yugan County	MAPZ	0.0372	−0.2363	0.1023	0.0272	−0.0174
Yujiang County	MAPZ	0.0000	0.0000	−0.1130	−0.1417	−0.0637
Anyi County	KEFZ	−0.0851	−0.0057	0.0034	0.0390	−0.0121
Fuliang County	KEFZ	0.0000	0.0000	−0.0330	0.0040	−0.0073
Wanli District	KEFZ	0.0000	0.0000	0.0000	0.0000	0.0000
Wuning County	KEFZ	0.0000	−0.2230	0.0555	−0.1022	−0.0674
Xingzi County	KEFZ	−0.1080	−0.0171	0.1251	−0.1594	−0.0398
Mean		−0.0206	−0.0758	−0.0036	−0.0226	−0.0306

The integrated energy consumption is selected as the energy input. All types of energy (coal, oil, and gas) are converted into the equivalent of tons of standard coal. For undesirable outputs, SO_2 emissions, wastewater, and soot emissions are used, since these types of data are available for the PLEEZ. We then collect the input and output data of the 38 counties for empirical analysis. All the data used are from the *Jiangxi Statistical Year Book* and *Statistics of Poyang Lake Eco-Economic Zone*. Table 1 reports the descriptive statistics of these data.

3.2. Regional heterogeneity in PLEEZ

The rapid economic development of China has impelled authorities to explore policies that prevent unreasonable land use, severe ecological damage, and uncoordinated development of urban and rural areas. Under this background, the State Council of China has formulated the Nationwide Major Function Oriented Zone policy.

In its development planning, the Jiangxi provincial government has divided Jiangxi province into three major types of functional zones: key development zones (KDZ), limited development zones (LDZ), and development prohibited zones (DPZ).

To use the metafrontier approach, the first step should be to characterize the groups and determine their members. In this paper, the Major Functional Zone classification is selected as the criteria for categorizing the groups based on their different development targets, i.e. economic development and urbanization levels Accordingly, the counties were divided into three types: key development zone (KDZ), major agriculture production zone (MAPZ) and key ecological function zone (KEFZ). The KDZs are urbanized areas with a high level of industrialization and high capital intensity. The MAPZs offer primary products with the principle of developing modern agriculture and ensuring the food security. The KEFZs maintain the ecosystem for its essential ecological functions. As shown in Table 3, in the PLEEZ, the KDZs include 23 counties, the MAPZs contain 10 counties, and the KZFZs include 5 counties. Fig. 1 illustrates the geographical location of each county with its major functional zone classification information.

In order to illustrate the heterogeneity in the PLEEZ, we compare the inputs and outputs across the three major functional zones (Table 2). Because soot and wastewater are in a situation similar to that of SO_2, we only list the information for SO_2. The KDZs have more capital and consume greater amounts of energy to produce GDP. The other two types of zones produce less GDP and use less energy and labor. The variables thus illustrate the widening gap between the KDZs and the other two types of zones. The KEFZs consume less energy and contribute less SO_2 emissions than the MAPZs because they are focused on ensuring ecological security.

3.3. Empirical results

3.3.1. Environmental productivity growth

We have calculated the GMLPI for each of the 38 regions in the PLEEZ to assess the environmental productivity change incorporating regional heterogeneity. Table 3 shows the empirical results of the GMLPI index for the 2009–2013 period. The GMLPI increased approximately 8.71% from 2009 to 2013 on average, which indicates that the PLEEZ area had a notable increase in environmental productivity after its establishment. Significant downward trends in the GMLPI appeared in 11 regions during the research period. Among those, Pengze county shows the largest decrease in GMLPI (−0.06). Other regions demonstrate varying

Table 5
Group technological change component of the GMLPI, 2009–2013.

Regions	Group	09–10	10–11	11–12	12–13	Mean
Changjiang District	KDZ	0.0602	0.3114	0.0192	0.0812	0.1180
Donghu District	KDZ	0.1289	0.4753	0.5794	0.5665	0.4375
Fengcheng City	KDZ	0.2034	0.2592	0.0008	0.0574	0.1302
Gaoan City	KDZ	0.0968	0.1264	0.0099	0.0770	0.0775
Gongqincheng City	KDZ	0.2159	0.2636	0.0407	0.3773	0.2244
Guixi City	KDZ	0.0720	0.0571	0.0705	0.1004	0.0750
Hukou County	KDZ	0.0745	0.0752	0.0017	0.0092	0.0402
Jiujiang County	KDZ	0.1633	0.1414	0.0461	0.0681	0.1047
Leping City	KDZ	0.0388	0.0883	0.0131	0.0573	0.0494
Linchuan District	KDZ	0.0667	0.1375	0.0069	0.0379	0.0623
Lushan District	KDZ	0.1123	0.1426	0.0139	0.0247	0.0733
Nanchang County	KDZ	0.1412	0.9345	0.0671	0.2994	0.3606
Pengze County	KDZ	0.1991	0.0989	0.0267	0.0217	0.0866
Qingshanhu District	KDZ	0.0463	0.0326	0.0000	0.0017	0.0202
Qingyunpu District	KDZ	0.0463	0.2670	0.0324	0.0624	0.1020
Ruichang City	KDZ	0.0168	0.0941	0.0439	0.0462	0.0503
Xihu District	KDZ	0.1284	0.6217	0.4899	0.5858	0.4565
Xinjian County	KDZ	0.0497	0.1390	0.0303	0.1446	0.0909
Xunyang District	KDZ	0.3050	0.2513	0.0733	0.1558	0.1963
Yushui District	KDZ	0.1199	0.0864	0.0744	0.0497	0.0826
Yuehu District	KDZ	0.0407	0.6737	0.1486	0.1672	0.2575
Zhangshu City	KDZ	0.1165	0.1035	0.0320	0.0473	0.0748
Zhushan District	KDZ	0.2179	0.3225	0.4438	0.2436	0.3069
Dean County	MAPZ	0.2742	0.2241	0.1785	0.2459	0.2307
Dongshan County	MAPZ	0.1233	0.0399	0.1961	0.1474	0.1267
Duchang County	MAPZ	0.1664	0.0173	0.1275	0.0357	0.0867
Jinxian County	MAPZ	0.1660	0.4084	0.4343	0.1614	0.2925
Poyang County	MAPZ	0.1656	0.1451	0.0631	0.1070	0.1202
Wannian County	MAPZ	0.0219	0.1841	0.3351	0.1684	0.1774
Xingan County	MAPZ	0.2140	0.0685	0.1282	0.0866	0.1243
Yongxiu County	MAPZ	0.1343	0.1047	0.1714	0.1423	0.1382
Yugan County	MAPZ	0.3095	0.0274	0.0497	0.0119	0.0996
Yujiang County	MAPZ	0.4023	0.4524	0.1623	0.1015	0.2796
Anyi County	KEFZ	0.1249	0.0357	0.0000	0.0376	0.0496
Fuliang County	KEFZ	0.0599	0.0463	0.0027	0.0244	0.0333
Wanli District	KEFZ	0.2610	1.1047	0.1176	0.0670	0.3876
Wuning County	KEFZ	0.2025	0.1164	0.0064	0.0346	0.0900
Xingzi County	KEFZ	0.0739	0.2481	0.0297	0.0525	0.1010
Mean	PLEEZ	0.1411	0.2349	0.1123	0.1239	0.1530

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degrees of growth. Xihu District, Nanchang County, and Donghu District show relatively high GMLPI growth rates. Average GMLPI grew yearly, especially during the 2009–2011 period (0.108). Interestingly, these results are different from a recent study investigating the effect of the PLEEZ on agricultural labor productivity (Wu and Wang, 2015), where the authors found that the establishment of the PLEEZ had negative impact on the agricultural labor productivity. This difference can reflect a major function of the PLEEZ—developing economy in an eco-/environmental friendly way—which should positively influence the environmental total-factor productivity; however, developing economy in an eco-/environmental friendly way does not mean an increase in the agricultural labor productivity.

3.3.2. Group efficiency change

The GMLPI is decomposed into three indices to investigate its growth patterns: group efficiency change (GEC), group technological change (GTC), and metafrontier gap change (MGC).

As shown in Table 4, the average group efficiency change (GEC) of the PLZZE is −0.0306 using the GMLPI estimate, suggesting that the environmental efficiency decreased approximately 3.06% per year during 2009–2013. At the regional level, 24 regions show a dip in GEC, while GEC grows only among 5 regions. In the other 9 regions, GEC is largely unchanged. Among all regions, the highest growth rate, 10%, is in Dongshan County. The growth rate of GEC in Pengze County is the lowest (−14.1%), indicating the county lags in environmental efficiency performance.

For the different functional zones, Nanchang County in a KDZ has the highest GEC, with an average of 8.25%, whereas the lowest GEC is marked by Pengze County. In the MAPZ, Dongshan County shows the highest GEC and the lowest one is Yujiang County (−6.37%). In the KEFZ, each region shows no improvement in GEC, with the lowest being Wuning County (−6.74%).

Table 6
Metafrontier gap change component of the GMLPI, 2009–2013.

Regions	Cluster	09–10	10–11	11–12	12–13	Mean
Changjiang District	KDZ	0.0000	0.0000	0.0000	−0.0025	−0.0006
Donghu District	KDZ	0.0000	0.0004	0.0000	0.0000	0.0001
Fengcheng City	KDZ	−0.0072	0.0240	−0.0013	0.0110	0.0066
Gaoan City	KDZ	−0.0069	0.0074	0.0012	0.0064	0.0020
Gongqincheng City	KDZ	0.0206	0.0028	0.0000	0.0000	0.0059
Guixi City	KDZ	0.0042	0.0027	0.0135	0.0000	0.0051
Hukou Prefecture	KDZ	−0.0020	0.0034	0.0000	0.0000	0.0004
Jiujiang Prefecture	KDZ	0.0528	−0.0807	0.0462	0.0067	0.0062
Leping City	KDZ	0.0662	0.0155	0.0114	0.0074	0.0251
Linchuan District	KDZ	0.0019	0.0029	0.0098	0.0055	0.0050
Lushan District	KDZ	0.0097	0.0045	0.0000	0.0001	0.0036
Nanchang Prefecture	KDZ	0.0110	0.0000	0.0002	0.0000	0.0028
Pengze Prefecture	KDZ	−0.0006	−0.0383	0.0100	0.0036	−0.0063
Qingshanhu District	KDZ	0.0000	0.0000	0.0000	0.0000	0.0000
Qingyunpu District	KDZ	0.0000	0.0000	0.0000	−0.0007	−0.0002
Ruichang City	KDZ	0.0894	0.0194	0.0129	0.0073	0.0323
Xihu District	KDZ	0.0000	0.0000	0.0000	0.0000	0.0000
Xinjian Prefecture	KDZ	0.1089	−0.0007	0.0075	−0.0046	0.0278
Xunyang District	KDZ	0.0000	−0.0033	−0.0079	0.0000	−0.0028
Yushui District	KDZ	0.0102	−0.0021	0.0000	0.0000	0.0020
Yuehu District	KDZ	0.0033	0.0642	0.0044	0.0000	0.0180
Zhangshu City	KDZ	0.0254	−0.0879	0.0249	0.0120	−0.0064
Zhushan District	KDZ	−0.0669	−0.1406	−0.1021	−0.0107	−0.0801
Dean Prefecture	MAPZ	−0.0191	−0.1524	−0.0301	−0.0938	−0.0739
Dongshan Prefecture	MAPZ	0.0326	−0.0571	−0.2455	−0.1793	−0.1123
Duchang Prefecture	MAPZ	0.0021	−0.1504	0.0329	−0.1312	−0.0617
Jinxian Prefecture	MAPZ	−0.0132	−0.1623	−0.3354	−0.1168	−0.1569
Poyang Prefecture	MAPZ	−0.0640	−0.2496	−0.0382	−0.1298	−0.1204
Wannian Prefecture	MAPZ	−0.0497	0.0144	−0.0353	−0.0377	−0.0271
Xingan Prefecture	MAPZ	−0.0405	−0.0713	−0.0298	−0.0341	−0.0439
Yongxiu Prefecture	MAPZ	−0.0504	−0.1781	−0.0274	−0.1352	−0.0978
Yugan Prefecture	MAPZ	0.0081	−0.0556	−0.0528	−0.0728	−0.0433
Yujiang Prefecture	MAPZ	−0.0377	−0.4174	−0.0684	0.0255	−0.1245
Anyi Prefecture	KEFZ	0.0400	0.0073	0.0094	−0.0397	0.0043
Fuliang Prefecture	KEFZ	−0.0214	−0.0262	−0.0404	−0.0181	−0.0265
Wanli District	KEFZ	−0.2367	−0.9453	−0.2180	−0.0656	−0.3664
Wuning Prefecture	KEFZ	0.0156	−0.1623	−0.0450	0.0601	−0.0329
Xingzi Prefecture	KEFZ	−0.3481	−0.0793	−0.0233	0.0295	−0.1053
Mean	PLEEZ	−0.0122	−0.0761	−0.0294	−0.0236	−0.0353

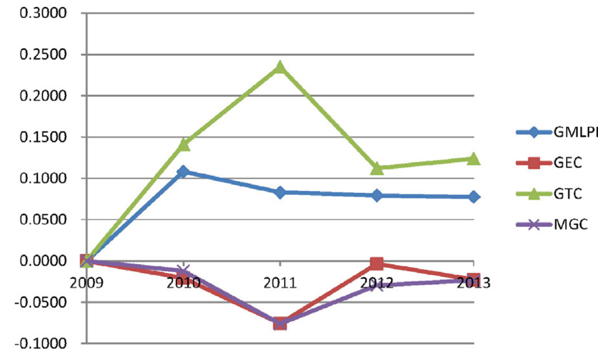

Fig. 2. GMLPI trend and decompositions.

3.3.3. Group technological change

Table 5 shows that the average GTC for all observations in the sample period is 0.1530, indicating that the regions experienced a significant improvement in technology, 15.3% on average. Only Qingshanhu District and Anyi County remained unchanged in technology during 2011–2012. A number of regions exhibited a sharp increase in technological change during 2010–2011, especially Wanli District (1.105), Yuehu District (0.674), and Xihu District (0.622).

We can conclude that the establishment of the PLEEZ stimulated eco-innovation in environmental-friendly production processes for most of the counties in the PLEEZ area.

3.3.4. Metafrontier gap change

Metafrontier gap change (MGC) measures the disparity between the environmental frontier of the PLEEZ and the environmental frontiers of the three groups. Thus, it can measure the technological heterogeneity across the three major functional zones. Table 6 shows that the average MGC is −0.035, implying that the technology gap between the group-frontier and metafrontier has widened by 3.5%. This may show that the PLEEZ region significantly lacks technological leadership effects during the sample period. From the functional zone perspective, there were no technological leadership effects in the MAPZs, while only one region (Anyi) in the KEFZs showed leadership effects. However many counties in KDZ showed a positive leadership effect.

3.4. Trends in GMLPI and its decompositions

Fig. 2 shows the cumulative trend in the GMLPI as well as its decompositions for the PLEEZ as a whole. An upward trend of the GMLPI is observed with an average growth rate exceeding 5% during 2009–2013. Meanwhile, there is a remarkable upward trend in GTC, indicating

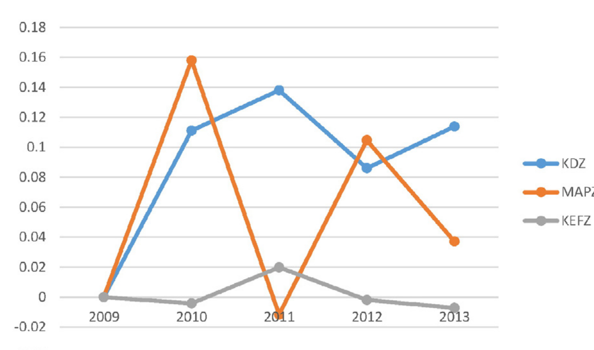

Fig. 3. GMLPI trends for the three major functional zones.

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Fig. 4. GEC trends of the three major functional zones.

Fig. 6. MGC trends for the three major functional zones.

that technological change was the main source of environmental productivity growth in the PLEEZ. We can conclude that environmental productivity is primarily driven by eco-innovation. The downward trend in both GEC and MGC is investigated in Fig. 2, which indicates a lack of eco-friendly catch-up and technological leadership effect in the PLEEZ.

We now compare the GMLPI and its decompositions across different major functional zones. Fig. 3 shows the trends of the GMLPI for the three major types of functional zones of the PLEEZ. The KDZs show values above zero and a continuously increasing trend in the GMLPI during 2009–2013. The MAPZs show an M-type trend, reflecting the fluctuations in the environmental productivity change. The KEFZs have a relatively flat trend near zero, indicating that the environmental productivity in this area remained almost unchanged.

The components of the GMLPI for the three major functional zones should be also investigated. First, the trends in GEC for the three zones are shown in Fig. 4. The GEC index of all three zones during 2009–2011 shows downward trends below zero, indicating that the distance between the observations and environmental technology frontier has grown. After 2011, the GEC of the three zones began to increase. The MAPZs and the KEFZs, with greater catch-up effect, showed efficiency gains in 2012, but the KEFZs and the KDZs exhibited falling GEC again in 2013.

Fig. 5 shows that GTC index of the three zones is above 0 during 2009–2013, indicating that eco-innovation occurred in the three zones. The KEFZs showed significant eco-innovation before 2011, a trend that became slow after 2011. The KDZs also show a similar pattern in GTC. The MAPZs exhibit an M-shaped pattern in GTC, reflecting fluctuations in eco-technological change in this zone.

In Fig. 6, MGC fluctuations of the KDZs is near zero, indicating that the MGC of the KDZs remained unchanged, suggesting that the technology gap of the KDZs is the same. In the MAPZs and the KEFZs during 2009–2011, the technology gap grew; while after 2011, MGC showed an upward trend, indicating that the technology gap of these two zones fell, especially for the KEFZs.

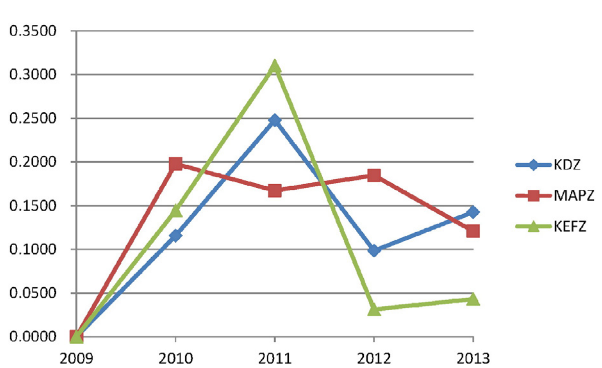

Fig. 5. GTC trends for the three major functional zones.

Combining the trends of the GEC, GTC, and MGC for three zones, the GMLPI appears to be largely connected to technological change. This suggests that the environmental productivity growth of the three zones also benefited from eco-innovation during this period.

3.5. Group innovators and meta-innovators in PLEEZ

There are two types of innovators: group innovators and metafrontier innovators. Time t denotes period t in which a region participates in constructing the production frontier. According to Zhang and Wei (2015), such a region should satisfy the following conditions:

$$TC>0 \tag{9a}$$

$$\vec{D}^{t}\left(x^{t+1}, y^{t+1}, b^{t+1}\right)<0 \tag{9b}$$

$$\vec{D}^{t+1}\left(x^{t+1}, y^{t+1}, b^{t+1}\right) = 0. \tag{9c}$$

Eq. (9a) suggests that the contemporaneous environmental technology frontier should shift toward intertemporal environmental technology, signaling the occurrence of eco-innovation. Eq. (9b) indicates that the production activity of innovative regions in period $t + 1$ should be outside the frontier of period t. Eq. (9c) implies that the innovative region should be located on the environmental technology frontier in period $t + 1$.

Two additional conditions are required to choose metafrontier innovative regions:

$$MGC>0 \tag{10a}$$

Table 7
Group innovators in the three zones.

Period	Group innovator		
	KDZ	MAPZ	KEFZ
2009–2010	Donghu District Xihu District	Jinxian Prefecture Poyang Prefecture Yujiang Prefecture	Fuliang Prefecture Wanli District Xingzi Prefecture
2010–2011	Yushui District Zhushan District	Jinxian Prefecture Poyang Prefecture Yujiang Prefecture	Fuliang Prefecture Wanli District Wuning Prefecture
2011–2012	Gongqincheng City Xihu District Xunyang District Zhushan District	Jinxian Prefecture Poyang Prefecture	Wanli District
2012–2013	Zhushan District	Jinxian Prefecture Wannian Prefecture	Wanli District

Table 8
Kruskal–Wallis test for three zones.

Test	Null hypothesis (H0)	Chi-square	p-Value
GMLPI	KDZ = MAPZ = KEFZ	4.17	0.124
GEC	KDZ = MAPZ = KEFZ	2.98	0.225
GTC	KDZ = MAPZ = KEFZ	8.46	0.015
MGC	East = Central = West	41.48	0.000

$$\overrightarrow{D}^G\left(x^{t+1}, y^{t+1}, b^{t+1}\right) = 0 \tag{10b}$$

Eq. (10a) states that a metafrontier innovator should be among the technological leaders, implying a decrease in the gap between the group frontier and the metafrontier. Condition (10b) suggests that a metafrontier innovative region should be located along the global environmental technology frontier.

Table 7 lists the innovators for every second year. No regions appear to satisfy the conditions of metafrontier innovators. This result confirms the findings in the previous sections: the lack of leadership effect in the PLEEZ. For group innovators, in the KDZs, Zhushan District and Xihu District are found to be innovators twice, respectively. In the MAPZs, Jinxian County constructed the group frontier in each period. In the KEFZs, Wanli County appeared four times as the group innovator.

Finally, to investigate any statistically significant differences among the three major zones in terms of the GMLPI and its decompositions, the non-parametric Kruskal–Wallis test is used, with the results shown in Table 8. The statistical test supports the hypothesis that, GTC and MGC, group-specific components, for the three major zones differ from each other significantly. On the other hand, the result failed to prove that the GMLPI and GEC, statistically have differences. It is found that the sources of regional heterogeneities are driven from technological-related terms, i.e. innovation and technological leadership in eco-development. The kernel density plot in Fig. 7 also implies obvious differences in the distribution pattern among the three major zones. In addition, the related kernel density test verifies significant differences in the distribution pattern.

4. Conclusion

This study investigated the effect of the establishment of the PLEEZ on regional environmental total-factor productivity growth using county level data for the period 2009–2013. By considering regional heterogeneity and the non-radial Luenberger productivity indicator, we presented the global metafrontier Luenberger productivity indicator (GMLPI) for measuring environmental productivity growth and its decompositions including eco-catching-up and eco-innovation. Results show that environmental productivity growth has increased by 8.71%, primarily driven by eco-technological change, implying that the establishment of the PLEEZ is effective in encouraging eco-innovation in the PLEEZE. However, the PLEEZ lacks eco-leadership effects because the metafrontier gap has not been reduced. The results also show that there are significant heterogeneities among the three major types of functional zones in the PLEEZ in environmental productivity growth and its patterns. The KDZ areas showed the highest environmental productivity growth and technological leadership change.

This empirical study has some limitations. Technically, the method shows a lack of statistical inference in the GMLPI. By using the bootstrapping method, statistical analysis of the productivity result could be included, making the results more robust.

Another limitation is that no statistical evidence is provided to support the policy implications because of the lack of data. In the future, if the data is available, econometric models should be used to investigate the factors affecting environmental productivity in the PLEEZ. In addition, since county level data of the PLEEZ is used in this study, the metafrontier can only partially address the heterogeneity problem. Given that firm-level data is available, this data should be used instead in the future.

Acknowledgements

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Appendix A

The Poyang Lake is the largest freshwater lake in China. Situated in the North of China's Jiangxi Province, the lake drains directly into the middle and lower reaches of the Yangtze River, thereby acting as a natural flood-buffer for the entire lower Yangtze hydrological system. Historically the Poyang Lake experienced devastating degradation of its

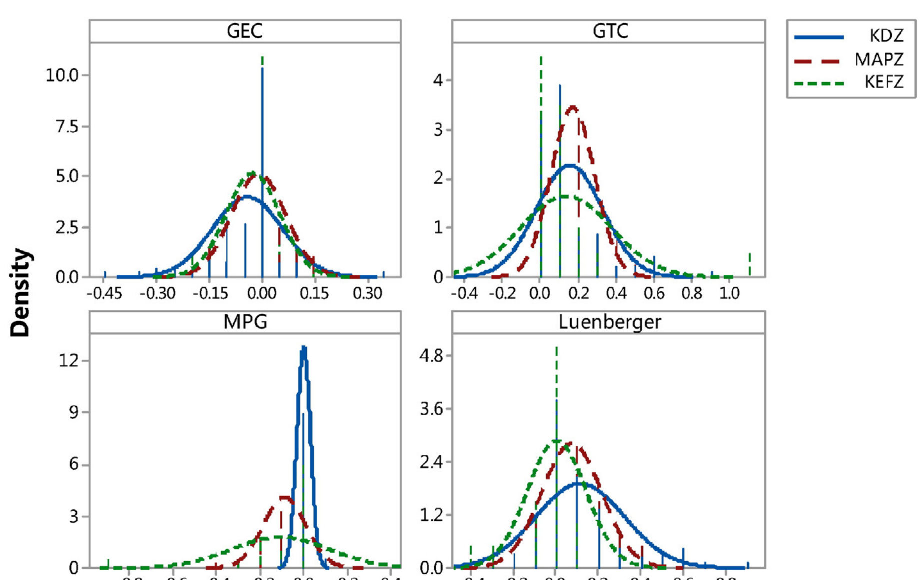

Fig. 7. Kernel density estimation of GMLPI and decompositions for three zones.

natural environment. In the 1980s the Jiangxi Provincial Government recognized the threats and decided to take actions to protect and to rehabilitate the natural environment of the province. In 1985 the Provincial Government set up a Mountain–River–Lake Sustainable Development Program in order to tackle these ecological problems. The Poyang Lake Eco-economic Zone is a further development plan of the Mountain–River–Lake Sustainable Development Program by considering new challenges. On December 12th 2009 the State Council of China approved the Poyang Lake Eco-economic Zone Plan as part of its National Strategy. This plan basically includes all three aspects of a sustainable development program: environmental protection, social development and economic growth. The Poyang Lake Eco-economic Zone is located in the North of Jiangxi Province, covering a total area of 51,200 km^2 (app. 30% of the province). The area covers three large cities and 38 counties with a population of >20 million (app. half of the province's population).

The entire Eco-economic Zone consists of three sub-zones. The core protection zone (5180 km^2) includes the lake's water body up to its maximum size and the directly connected wetland. Environmental protection will be the high priority here; consequently economic activities have to follow rigorous regulations. The lakeshore zone surrounds the core protection zone by a radius of 3 km covering an area of 3750 .km^2. Strict regulations are applied to limit all economic development in this sub-zone. The development zone covers the largest part of the Poyang Lake Eco-economic Zone, with an area of 42.200 km^2. Economic development and growth are a priority in this area; however all economic development activities in this zone follow environment-friendly rules.

The Poyang Lake Eco-economic Zone is a strategic development plan to improve Jiangxi Province's sustainable development. In order to achieve this goal, the implementation of this plan splits up into short term (2009–2015) and long term stages (2016–2020).

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