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Determinants of stagnating carbon intensity in China

Dabo Guan[1,2]*, Stephan Klasen[3], Klaus Hubacek[4], Kuishuang Feng[4], Zhu Liu[5], Kebin He[6], Yong Geng[7] and Qiang Zhang[1]*

China committed itself to reduce the carbon intensity of its economy (the amount of CO_2 emitted per unit of GDP) by 40–45% during 2005–2020. Yet, between 2002 and 2009, China experienced a 3% increase in carbon intensity, though trends differed greatly among its 30 provinces. Decomposition analysis shows that sectoral efficiency gains in nearly all provinces were offset by movement towards a more carbon-intensive economic structure. Such a sectoral shift seemed to be heavily affected by the growing role of investments and capital accumulation in China's growth process which has favoured sectors with high carbon intensity. Panel data regressions show that changes in carbon intensity were smallest in sectors dominating the regional economy (so as not to endanger these large sectors, which are the mainstay of the provincial economy), whereas scale and convergence effects played a much smaller role.

The Kyoto Protocol's first commitment period (2008–2012) has ended and the world is still in the process of negotiating a new global agreement on reductions in global emissions to minimize the risk of anthropogenic climate change[1]. Effective participation of developing countries is vital to achieve this goal, as they have been responsible for nearly all of the growth of global emissions in the past decade and are projected to increase their emissions substantially in coming decades. In the Copenhagen Accords[2], major emerging economies such as China and India have announced their climate targets, focusing on improving their carbon intensities. China, the world's largest emitter of CO_2 emissions, committed to reduce its carbon intensity by 40–45% relative to 2005 levels by 2020[3]. In addition, in the 12th Five Year Plan (2010–2015) the Chinese government set a 17% reduction in carbon intensity while maintaining at least 8% annual GDP growth during that time period[4]. Each of 30 Chinese provinces were allocated mandatory targets. Such efficiency gains would cumulatively save about 1.4 billion tonnes of coal consumption between 2006 and 2015, reducing CO_2 emissions by more than 3 billion tonnes, or equivalent to 40% of Chinese emissions in 2010[5]. A growing literature has used various quantitative modelling techniques to illustrate how carbon intensity reduction targets can be best allocated across China's provinces based on socioeconomic equities[6–11]. There are, however, no studies about the determinants of provincial carbon intensity changes in China. This paper analyses the determinants of carbon intensity changes at the level of economic sectors in China's provinces.

There are two main strategies for improvements in carbon intensity[12]. First, a reduction of emissions per unit of output in each sector can be achieved, either through the deployment of low-carbon technologies and retrofitting (for example, switching conventional technology to integrated gasification combined cycle in coal-fired plants) or through economies of scale—enlarging the production capacity and with it the production processes that become overall more efficient and less carbon-intensive per unit of output. Second, carbon intensity can be reduced by means of a change in the sectoral structure towards sectors with lower carbon intensity (for example, transforming from a manufacturing-based economy to a services-based economy).

Heavy capital investment has been the main approach to maintain high economic growth for China since 2000. As a result, large-scale investments have been made in energy-intensive industries such as coal-fired electricity generation, metal processing and cement production owing to domestic demand for construction materials[13]. The proportion of emission-intensive production in total economic outputs increased significantly for the nation as well as almost all its provinces. However, it is unclear what role changes in the industrial structure played vis-à-vis improvements in carbon intensity within each sector and what were the drivers for the respective changes.

Within this overall context, this paper has two aims. First, to understand to what extent the two ways of changing the regional carbon intensity have played a role in the changing carbon intensity of production in Chinese provinces by using decomposition analysis (Methods). Second, to understand the drivers of changes in carbon intensity by sector and province using a panel regression approach (Methods). This paper has chosen 2002–2009 as the study period. China entered the World Trade Organization in 2002 and thereafter achieved double digit economic growth by extensive production expansion for exports and capital investments. Since the global economic recession started in 2007, leading to declining consumption levels in western countries, China has maintained strong economic growth by heavy investment on capital accumulation. By 2009, capital accumulation contributed half of

[1]Tsinghua-Leeds Joint Low Carbon City Research Programme, Ministry of Education Key Laboratory for Earth System Modelling, Centre for Earth System Science, Tsinghua University, Beijing 100084, China, [2]School of International Development, University of East Anglia, Norwich NR4 7TJ, UK, [3]Department of Economics, University of Göttingen, Göttingen 37073, Germany, [4]Department of Geographical Sciences, University of Maryland, College Park, Maryland 20742, USA, [5]Sustainability Science Program and Energy Technology Innovation Policy Project, John F. Kennedy School of Government, Harvard University, Cambridge, Massachusetts 02138, USA, [6]State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, China, [7]School of Environmental Science and Technology, Shanghai Jiao Tong University, Shanghai 200240, China.
*e-mail: dabo.guan@uea.ac.uk; qiangzhang@tsinghua.edu.cn

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national GDP (ref. 14), up from 36% in 2000. This means that 95% of China's GDP growth in 2009 was contributed by capital accumulation, whereas household consumption stayed relatively stable and exports decreased significantly[15,16].

Determinants of regional changing carbon intensity

The carbon intensity of an economy is determined by two factors—the carbon intensity of each sector and the sectoral structure of the economy. Ideally, both factors would lead to an improvement of carbon intensity, but what we see on the national level is that improvements in carbon efficiency (amount of GDP per unit of CO_2 emission, the inverse of carbon intensity) in some sectors were over-compensated by increases in production, especially of dirtier sectors. For example, during 2002–2009, the carbon efficiency of China's coal-fired power plants improved by 10%, whereas its production capacity more than doubled and its share in the total economy also increased. Similar trends can be observed in other carbon-intensive industries. National data shows that China's overall carbon intensity increased slightly by 3% during 2002–2009, placing China on a trajectory leading away from its ambitious carbon intensity improvement goals. But this overall trend disguises a more interesting and contradictory picture between Chinese regions: there were 18 of the 30 Chinese provinces (excluding Tibet, Hong Kong, Macao and Taiwan) that achieved a net improvement in carbon intensity during the study period.

The carbon efficiency improvements usually occurred in the economically advanced coastal provinces as well as in the heavy industrial inland regions, but owing to different causes. In contrast, a few economically poor provinces show large increases in their regional carbon efficiency. Figure 1 enables the simultaneous visualization of the scale of changes in regional carbon efficiency, strength of sectoral carbon efficiency gains, and production structural changes among 30 Chinese provinces. Most of bubbles are located in the top-right quadrant. This indicates that most Chinese regions improved their sectoral carbon efficiency but also expanded their emission-intensive production simultaneously. The size of the bubbles determines the scale of regional carbon efficiency gains. A white bubble represents that the province had achieved efficiency improvements (that is, a reduction in carbon intensity) during 2002–2009; whereas a black bubble denotes efficiency loss (that is, an increase in carbon intensity). There are four distinct patterns describing the competition between achievements in improving sectoral carbon efficiencies and production structure shifts towards more carbon-intensive sectors.

First, carbon efficiency at the sectoral level improved while the production structure became 'greener'. This occurred in only the two richest coastal provinces—Guangdong and Jiangsu (shown by the white bubbles in the bottom-right quadrant). They implemented low-carbon technologies and, at the same time, decreased the share of emission-intensive production. For example, improvements in carbon efficiency at the sectoral level allowed respective 22% and 10% improvements in overall carbon efficiency performance in the two regions; at the same time, they achieved some further gains from decarbonizing their production structures.

Second, a carbonizing production structure counter-balanced some of the sectoral carbon efficiency gains. The 45-degree line in the top-right quadrant of Fig. 1 represents an even strength by both determinates in affecting regional carbon intensity changes. Beijing is represented by a white bubble located below the 45-degree line. The carbon efficiency among Beijing's production sectors improved by 54%; however this was compensated by a 27% loss due to the carbonization of Beijing's production structure. This finding is further supported by the fact that the carbon efficiency for producing electricity and heavy machinery improved by 80% and 45%, respectively, although outputs of these two relatively carbon-intensive sectors increased two- and tenfold, respectively. At the same time, many newly industrialized interior economies experienced even more marked changes to their economies. The white bubbles for Inner Mongolia and Ningxia (both in Northwest China) are at the far end of the top-right quadrant in Fig. 1, which denotes that both improvements in sectoral carbon efficiency as well as shifts towards carbon-intensive sectors were substantial during 2002–2009. For example, taking advantage of abundant energy and other mineral resources, mainly coal, Inner Mongolia had been pursuing a development plan based on highly energy-intensive industrial clusters (for example, resources mining, electricity generation, metal smelting and processing). Inner Mongolia shut down many carbon-intensive but inefficient small-scale metal smelting mills and replaced them with large-scale modern factories[17]. The production capacities of metal smelting and cement production had increased 14-fold during 2002–2009. To fulfil the electricity demand for the rapid development of heavy industries and other economic activities, Inner Mongolia increased thermal electricity production from 5 TWh (Terawatt hours) in 2002 to 22 TWh in 2009. Technological advancement brought 159% sectoral efficiency improvements, although those efforts were offset by a 141% loss due to the carbonizing production structure, resulting in a mere 18% net efficiency gain of Inner Mongolia's economy. Large-scale expansion of heavy industries in Inner Mongolia is largely driven by China's interregional cooperation in manufacturing patterns (for example, sending preliminarily processed products from western provinces to eastern provinces for further processing). In 2007, 35% of industrial production in Inner Mongolia was exported to other provinces: in particular, two-thirds of processed metals, half of chemical products and 43% of cement (worth 158 billion Yuan or 15% of regional GDP) were mainly sent to coastal provinces to fulfil their production and consumption activities.

Third, a carbonizing production structure more than outweighs effects from improvements of sectoral carbon efficiency. Some interior economies that were following the national Great Western Development Plan, such as Guizhou and Yunnan in Southwest China, taking advantage of abundant coal resources, quickly developed emission-intensive production—that is coal mining and coking. Those regions are represented as black bubbles located

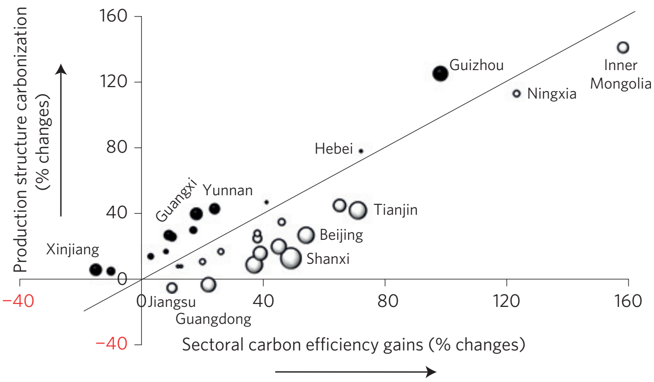

Figure 1 | The four quadrants show the relationship between two factors in driving regional carbon efficiency changes among 30 Chinese provinces. The *x* axis represents sectoral carbon efficiency improvements (from left to right). The *y* axis represents production structure carbonization (from bottom to top). The 45-degree line divides outcomes of carbon efficiency competitions (presented by bubbles) between sectoral carbon efficiency improvements and production structure changes among 30 provinces during 2002–2009. A white bubble represents net carbon efficiency gain of a provincial economy. A black bubble represents net carbon efficiency loss of a provincial economy. The size of a bubble represents the percentage change of a province's carbon efficiency during 2002–2009. Full data are available in Supplementary Table 1.

above the 45-degree line in the top-right quadrant. For example, the carbon efficiency of the coking sector in Guizhou had improved by 60% since 2002, while production increased by a factor of 11, leading to a threefold increase in electricity generation. Although technological changes would have generated a 98% gain in carbon efficiency of Guizhou's economy during 2002–2009, the carbonization of production structure had led to a 125% loss. As a consequence, the net carbon efficiency of the province reduced by 27%. A similar pattern can also be observed in other less developed provinces, such as Guangxi and Yunnan (Supplementary Table 1 and Fig. 1). However, the emission-intensive production in those provinces was to fulfil consumption elsewhere. Over one-third of Guangxi's GDP (119 billion Yuan) in 2007 was contributed by production for exports to other provinces. Processed metals and cement accounted for almost half of Guangxi's exports of industrial goods. Embodied CO_2 emissions flux from less developed western regions to developed coastal regions amounted to 243 million tonnes in 2007[18,19].

Fourth, there are provinces where both factors accumulate to increase the carbon intensity of production overall. Xinjiang and Hunan fall into this category and are represented by black bubbles in the bottom-left quadrant. In this case, these least-developed regions initialized their industrialization with small-scale emission-intensive production using outdated production technologies. For example, Xinjiang doubled its coal-fired electricity generation capacity, of which a large amount is from small-scale power plants (<135 MW; ref. 20), to match the demand of small-scale metal processing mills in remote areas. Although carbon intensity had decreased by 50% in metal smelting, its production scale increased sevenfold. Furthermore, China invested heavily in oil exploitation in Xinjiang, doubling the share of petroleum extraction and processing sectors in total industrial output. Therefore, carbon efficiency of Xinjiang's economy had declined 21% overall, of which 15% was contributed by sectoral carbon efficiency loss and 6% from production structure change during 2002–2009.

Determinants of changing sectoral carbon intensities

The above section quantifies how changes in sectoral carbon efficiency and economic structural change affect regional carbon intensity. We further investigate what determines changes in the carbon intensity of sectors in Chinese regions using a panel regression framework. Table 1 shows the results. The first column includes only initial sectoral carbon intensity, the initial sectoral output share, and the growth rate of the sectoral output as covariates. Again, there are four distinctive patterns driving the changes of sectoral carbon intensities among Chinese regions.

First, the initial sectoral emission intensity has a significant negative effect on sectoral growth of emissions, suggesting a convergence of sectoral emission intensities. This would be consistent with the idea of low-carbon technologies spreading to sectors that have started with high carbon intensities. But the effect is quantitatively not very large: a one standard deviation increase in the initial emission intensity reduces the carbon intensity in that sector by about 3%.

Second, sectoral output growth is also associated with declines in sectoral emission intensity. Increasing the production scale within a sector leads to reductions in carbon intensity. This effect is also significant, but quantitatively not very large. A one standard deviation of increase in production leads to about a 3% reduction in carbon intensity. But note that, given the massive growth that took place in China, one standard deviation amounts to a 360% increase in production. In fact, the mean sectoral production increase between 2002 and 2009 is 198% (Supplementary Table 1) among 30 provinces. For such a massive increase in the scale of production, the intensity improvements associated with these scale effects are rather modest.

Third, the initial share of the sector in total output has a sizeable and significant impact on changes in sectoral carbon intensities. A one standard deviation increase of the 2002 sectoral output share (equivalent to a 4% point increase in the share of the sector) would increase carbon intensity by 8%. It thus seems that large sectors were laggards in reducing carbon intensities. This is probably due to these large—and thus important—sectors experiencing less political pressure to reduce their carbon intensities. In many cases, their carbon intensities increased in the dash to raise or maintain high provincial growth rates. The second column also includes provincial dummy variables (with Shanghai being the omitted province). The effects of the main three covariates are hardly affected, but there are interesting additional effects. In particular, the three Northern provinces of Beijing, Tianjin and Hebei stand out for reductions in their sector carbon intensity above and beyond the effects of the other covariates, suggesting that significant efforts to implement low-carbon technologies had played an important role. In contrast, in Sichuan, Shandong, Henan and Shanxi, improvements in carbon intensity were significantly lower than in Shanghai, the omitted province, over and above the effects of initial carbon intensity, sector shares and sectoral growth. This suggests particularly small efforts to reduce carbon intensities there. In the third column of Table 1, we add interaction terms of the sector share with three regional dummy variables to examine whether the effect of the large initial sector share differs by region. We include interactions of Western, Central and Coastal provinces with the initial sector share, with Northeast being the omitted category (see Supplementary Table 4 for allocation of provinces to regions). We find that the effect of the initial sector share is particularly large in the Western and Central provinces (economically less advanced than Coastal provinces), where it is 50% larger than on average. This suggests that, in those Western and Central provinces, large sectors were allowed to grow without much concern for reducing carbon intensity, whereas this was much less the case in Coastal and, particularly, in North-Eastern provinces.

Fourth, we investigate the factors affecting sectoral growth, which is the second key determinant of the changing carbon intensity of a province as it affects the production structure of the province. In nearly all provinces, sectoral shifts took place towards more carbon-intensive sectors. The last column of Table 1 shows a regression of sectoral growth on initial sectoral emission intensity and initial output share of the sector, controlling for provincial-specific effects. We indeed confirm that sectors with a high initial emission intensity have grown faster, as have sectors with an initially high sectoral share. It thus seems that the dash for growth focused on large and emission-intensive sectors, thereby counteracting the carbon intensity improvements within sectors.

Sense and sensibility of China's capital investments

Capital accumulation is a key final demand sector that serves to boost regional economic growth as well as carbonizing China's economic structure. Capital accumulation has been the most effective and reliable tool to maintain China's strong GDP growth[12] even during the global economic recession. China initiated a 4 trillion Yuan (~US$600 billion) economic stimulus plan in 2008, 45% of which was designated for railroads, highways and power grids; and in total about 85% of the investments were used for infrastructure related construction. Capital investment creates a market demand for the large-scale production expansion of cement, steel and other highly emission-intensive processed materials, and associated electricity generation to support their production[13,21].

These capital investments triggered expansion in other sectors across China's provinces that provide key inputs. For example, cement production had increased at an annual rate of 15% since 2000 and reached almost 2 billion tons in 2009. Thus China is the world's largest producer of cement, accounting for 56% of the global total, which is about nine times the amount of the second largest

Table 1 | Drivers of sectoral emission intensities and sectoral growth.

	(1)	(2)	(3)	(4)
Dependent variable	**Ratio of 2009 to 2002 sectoral emission intensity**	**Ratio of 2009 to 2002 sectoral emission intensity**	**Ratio of 2009 to 2002 sectoral emission intensity**	**Ratio of 2009 to 2002 sectoral output**
Constant	0.511***	0.497***	0.528***	2.659***
	0.022	0.068	0.069	0.274
2002 sectoral emission intensity	−0.006***	−0.006***	−0.006***	0.050**
	0.002	0.002	0.002	0.024
2009/2002 sectoral output	−0.006**	−0.006*	−0.006**	
	0.003	0.003	0.003	
2002 sectoral output share	1.869***	1.890***	−0.021	−10.099***
	0.374	0.357	0.790	3.242
2002 sectoral output share* western			2.678***	
			1.032	
2002 sectoral output share* central			2.240**	
			1.067	
2002 sectoral output share* coastal			1.129	
			0.908	
Beijing		−0.243***	−0.245***	−0.033
		0.084	0.080	0.368
Tianjing		−0.180***	−0.182**	2.177
		0.083	0.081	1.890
Heilongjiang		−0.005	0.032	−0.798***
		0.085	0.093	0.285
Jilin		0.017	0.054	0.020
		0.086	0.088	0.436
Liaoning		0.056	0.093	0.266
		0.088	0.095	0.332
Hebei		−0.070	−0.113	0.329
		0.082	0.089	0.340
Shandong		0.193**	0.150*	1.395***
		0.085	0.091	0.363
Jiangsu		0.072	0.069	0.234
		0.086	0.086	0.331
Zhejiang		0.008	0.006	−0.076
		0.084	0.083	0.295
Guangdong		0.024	0.022	0.330
		0.095	0.094	0.298
Fujian		0.011	0.009	−0.352
		0.101	0.101	0.335
Hainan		−0.678	−0.067	4.614
		0.113	0.114	3.918
Anhui		0.048	0.004	0.119
		0.106	0.113	0.343
Henan		0.165	0.122	0.646*
		0.096	0.101	0.346
Hubei		0.036	−0.007	−0.401
		0.100	0.106	0.379
Hunan		0.032	−0.011	0.062
		0.085	0.092	0.340
Shanxi		0.172	0.129	0.225
		0.114	0.120	0.402
Jiangxi		0.035	−0.009	0.963*
		0.113	0.111	0.504

Continued

Table 1 | (continued)

Shaanxi		−0.143 0.090	−0.201** 0.091	0.770 0.548
Gansu		−0.104 0.089	−0.162* 0.092	0.009 0.503
Ningxia		−0.025 0.113	−0.085 0.109	1.427 1.037
Innermongolia		0.035 0.106	−0.023 0.109	1.779*** 0.639
Xinjiang		0.042 0.112	−0.016 0.118	0.799 1.183
Sichuan		0.297*** 0.096	0.239** 0.100	0.774* 0.458
Guangxi		−0.044 0.109	−0.103 0.112	0.100 0.400
Guizhou		−0.027 0.108	−0.086 0.111	0.277 0.509
Chongqing		−0.033 0.097	−0.091 0.102	0.496 0.408
Qinghai		0.026 0.134	−0.036 0.134	0.944 0.888
Yunnan		−0.006 0.113	−0.066 0.118	0.212 0.623
R^2	0.055	0.125	0.134	0.059
N	815	815	815	815

The table shows panel regression results of the drivers of changes in sectoral emission intensities in Chinese provinces between 2002 and 2009. The dependent variable represents the ratio of carbon intensity in 2009 over the carbon intensity in 2002 in a particular sector in a particular region (for example, the machinery sector in Tianjin). Values above one imply increasing the carbon intensity of production, values below one indicate reductions in carbon intensity. The independent variables include the initial carbon intensity of that sector, the growth of the sector, and the initial size of the sector in the overall output mix. Column (1) only uses these covariates. Column (2) presents regression results that also include province-specific fixed effects which might give a clue to province-specific policies that have contributed to reductions in sectoral carbon intensities (with Shanghai being the omitted reference category). Column (3) additionally interacts initial sector share with regional dummy variables (with North-East being the omitted region). Column (4) investigates correlates of sectoral output growth. Table shows coefficients (top number) and heteroscedasticity-corrected standard errors (bottom number) for each covariate. **P* value of 10%, ***P* value of 5%, ****P* value of 1%.

producer—India[22]. Almost all produced cement is domestically consumed (for example, 1.9 billion tons in 2009). A similar story can be told for steel production and consumption. Heavy investments in emission-intensive industries are usually long-term investments with durable production facilities. This would lock many Chinese regions specializing in these sectors into long-term emission-intensive economic production cycles. In fact, the cumulative production capacity of construction materials is in search for consumption, which will have to be mainly absorbed domestically in China, as international trade of cement was constantly about 130 ∼ 160 million tons per year (average of 2002 ∼ 2010; ref. 22), which would have been able to absorb up to only 8% of Chinese capacity in 2010[15].

This investment-led growth was promoted by the national and provincial political and administrative system. China's national government sets both climate and economic targets and uses these criteria in evaluating the performance and promotion of local government leaders[23]. Among the two targets, GDP always comes as a priority. The evaluation system is based on annual statistics and the tenures of many local government leaders are less than three years.

Policy enables technology-driven efficiency gains

Over the past decade, China has imported and begun to manufacture domestically many state-of-the-art low-carbon technologies[24]. For example, 38% of the world's newly constructed or operated super-critical and ultra-super-critical power plants are in China; and the main components such as boilers, turbines and generators are produced domestically[25]. However, these advanced technologies are usually retained in a small number of state-owned enterprises in the more advanced regions. In other words, the authorities can greatly influence technology transfer or even provide direct accessibility to low-carbon technologies. In principle, the national government can co-ordinate design and implement effective mechanisms and channels to encourage technology transfer between the more and less developed regions of China[26]. This is under-tested and can possibly be achieved by the current pilot domestic emission trade scheme (ETS; ref. 27), which would effectively link with the less developed interior regions through the use of emission caps and trade permits. A recent study shows that such an emission trade scheme is crucial to achieve a cost-effective intensity reduction by 2020[28]. China's carbon price would reach 99 Yuan per tonne of CO_2 by 2020 if China keeps ETS within the currently enrolled seven provinces, but the price will reduce by almost half if the ETS can be applied nationally[28].

An emission cap will maximize the carbon intensity improvements from technology deployment rather than from the economics of scale effects, thus preventing further carbonization of the structure of the economy. This mechanism would stimulate green business investments in the field of clean technology, and transfer these to the less and least developed regions, so that the international and domestic supply chain can be gradually decarbonized. Such coupled emission trade scheme (between European Union (EU) and Chinese regions) should be initialized by regional policy dialogues between the EU and China but implemented, regulated and closely monitored with the MRV (measurement, reporting and verification) processes by local governments and internationally independent monitoring agencies.

Current carbon reduction targets for each province are relative (that is, carbon intensity) and not absolute outcomes (that is, overall reduction of CO_2 emissions). The recent past has convincingly shown that implementation of intensity targets were not able to slow down overall carbon emissions growth. Thus absolute emission targets should be given priority over intensity targets. This needs to be accompanied by reform of the administrative regulatory and promotion system that favours economic growth without due environmental consideration. Technology development and deployment of renewable energy and *in situ* development of the circular economy should be treated as an integral part of sustainable economic development in Chinese regions[5].

Looking beyond China, this analysis shows the pitfalls and difficulties of adopting carbon intensity targets in emerging countries that are pursuing high rates of economic growth at the same time, which is also the situation in other emerging economies. Such carbon intensity targets may do little to curb absolute emissions in a situation of high growth; moreover, it may not even be possible to meet those carbon intensity targets when governments are at the same time providing strong incentives to sub-national governments to improve their growth performance, which is then often achieved in a very carbon-intensive way.

Methods

We develop a decomposition technique to measure the significance of the two factors (efficiency improvements within sectors and production structure changes) in driving carbon intensity changes. The carbon intensity of a regional economy can be illustrated as: $c = \mathbf{f} \times \mathbf{p}$, where c represents the carbon intensity of the entire economy (scalar); **f** is row vector of sectoral carbon efficiency (amount of GDP per unit of CO_2 emission); and **p** is a column vector of the proportion of each sector's production output to the total output of the regional economy (measured by percentages).

The Δc (the absolute change of c) is decomposed between two time points (2009 and 2002), into changes of the driving forces, **f** and **p**. However, there is no unique solution for the decomposition[21,29–31]. As our purpose concerns only two factors, the Marshall–Edgeworth index can be used to ensure a complete decomposition without any residual terms[32], which is shown in equation (1). In the case of n factors, the number of possible 'complete' decompositions (without any residual terms) is equal to $n!$ (ref. 30). A detailed description of different decomposition methods and their related non-uniqueness issues is provided in the Supplementary Information.

$$\Delta c = \frac{1}{2}\Delta \mathbf{f} \times (\mathbf{p}_{2002} + \mathbf{p}_{2009}) + \frac{1}{2}\Delta \mathbf{p} \times (\mathbf{f}_{2002} + \mathbf{f}_{2009}) \quad (1)$$

We apply equation (1) to conduct decomposition analysis for 30 provinces in China. Two sets of data are collected and compiled for every province. First, the industrial output data in 42 economic sector details for years 2002 and 2009 are obtained from the provincial statistical yearbooks for 2003 and 2010. Second, to produce **f**, we need to estimate CO_2 emission for every province in 42 economic sector details based on the provincial energy consumption by industry sectors. The energy data was extracted and converted to emission data for the 30 provinces individually and stem mainly from three Chinese statistics sources: (1) Chinese Energy Statistics Yearbook[33,34], which provides energy balance sheets for every province, (2) China Economic Census Book 2008[35], which provides final energy consumption in industrial sector details in 2008, and (3) Regional Statistics Yearbook 2003, which provides final energy consumption in sectoral details in 2002. However, the availability of final energy consumption data at the sector level varies between Chinese provinces. We have implemented a set of compilation and normalization processes to configure the energy data set for every province that consists of 18 types of fuel, heat and electricity consumption in physical units. We are aware of the significant statistical difference in terms of national and provincial energy statistics[36], and we adopt provincial energy data sets and follow the same data compilation and CO_2 emission calculation procedure as our previous study[13,37–40]. The details are provided in Supplementary Information.

Using these same data, we conduct panel regression analysis of the determinants of the percentage change in the carbon intensity of a sector in a region. We have 815 valid data points, each representing the ratio of the carbon intensity in 2009 over the carbon intensity in 2002 in a particular sector in a particular region (for example, the machinery sector in Tianjin). Values above one imply increasing the carbon intensity of production (that is, declining efficiency), values below one refer to reductions in carbon intensity (that is, improving efficiency). This is our dependent variable—our independent variables include the initial carbon intensity of that sector. Our expectation is that sectors with high carbon intensity are likely to lower the intensity level more over time owing to the spread of improved technologies. The second independent variable is the growth of the sector. As suggested above, reductions in carbon intensity can be achieved by increasing the scale of production, as large-scale operations are often more energy efficient and thus emit less carbon per unit of output. The third variable is the initial size of the sector in the overall output mix. The hypothesis here is that large sectors might have seen smaller improvements in carbon intensity, as these sectors are very important for the regional growth process. We present regression results that also include province-specific fixed effects which might give a clue to province-specific policies that have contributed to reductions in sectoral carbon intensities. We present pooled panel regressions but, in robustness checks, also control for sector-specific random effects (based on specification tests); the results are always very similar and therefore not shown here (but available on request). We always correct our standard errors for heteroscedasticity.

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References

1. Intergovernmental Panel on Climate Change *Climate Change 2007: Synthesis Report* (IPCC, 2007).
2. UNFCCC *Part Two: Action taken by the Conference of the Parties at its fifteenth session* (United Nations Framework Convention on Climate Change, 2010).
3. Geng, Y. Eco-indicators: Improve China's sustainability targets. *Nature* **477,** 162 (2011).
4. Qiu, J. China unveils green targets. *Nature* **471,** 149 (2011).
5. Liu, Z. *et al.* Energy Policy: A low-carbon roadmap for China. *Nature* **500,** 143–145 (2013).
6. Yi, W-J., Zou, L-L., Guo, J., Wang, K. & Wei, Y-M. How can China reach its CO_2 intensity reduction targets by 2020? A regional allocation based on equity and development. *Energy Policy* **39,** 2407–2415 (2011).
7. Wang, K., Zhang, X., Wei, Y-M. & Yu, S. Regional allocation of CO_2 emissions allowance over provinces in China by 2020. *Energy Policy* **54,** 214–229 (2013).
8. Wei, C., Ni, J. & Du, L. Regional allocation of carbon dioxide abatement in China. *China Econ. Rev.* **23,** 552–565 (2012).
9. Yuan, J., Hou, Y. & Xu, M. China's 2020 carbon intensity target: Consistency, implementations, and policy implications. *Renew. Sust. Energy Rev.* **16,** 4970–4981 (2012).
10. Dong, F., Long, R., Chen, H., Li, X. & Yang, Q. Factors affecting regional per-capita carbon emissions in China based on an LMDI factor decomposition model. *PLoS ONE* **8,** e80888 (2013).
11. Zheng, X., Yu, Y., Wang, J. & Deng, H. Identifying the determinants and spatial nexus of provincial carbon intensity in China: A dynamic spatial panel approach. *Reg. Environ. Change* **14,** 1651–1661 (2014).
12. Guan, D. & Barker, T. S. Low Carbon Development in the least developed region: A case study of Guangyuan, Sichuan province, southwest China. *Nat. Hazards* **62,** 243–254 (2012).
13. Minx, J. C. *et al.* A Carbonizing Dragon: China's fast growing CO_2 emissions revisited. *Environ. Sci. Technol.* **45,** 9144–9153 (2011).
14. Krugman, P. *The New York Times* (18 December 2011).
15. National Bureau of Statistics *China Statistical Yearbook 2010* (China Statistics Press, 2011).
16. Peters, G., Guan, D., Hubacek, K., Minx, J. & Webber, C. Effects of China's economic growth. *Science* **328,** 825–826 (2010).
17. Wang, Q. & Chen, Y. Energy saving and emission reduction revolutionizing China's environmental protection. *Renew. Sust. Energy Rev.* **14,** 535–539 (2010).
18. Feng, K. *et al.* Outsourcing CO_2 within China. *Proc. Natl Acad. Sci. USA* **110,** 11654–11659 (2013).
19. Meng, B., Xue, J., Feng, K., Guan, D. & Fu, X. China's inter-regional spillover of carbon emissions and domestic supply chains. *Energy Policy* **61,** 1305–1321 (2013).
20. An, H. & Nu, L. Xinjiang thermal power industry SO_2 D∼charge present situation and control countermeasure [in Chinese]. *Environ. Prot. Xinjiang* **27,** 22–25 (2005).
21. Peters, G., Webber, C., Guan, D. & Hubacek, K. China's growing CO_2 emissions—a race between lifestyle changes and efficiency gains. *Environ. Sci. Technol.* **41,** 5939–5944 (2007).
22. International Cement Review *The Global Cement Report Ninth Edition.* (Tradeship Publications Ltd, 2011).
23. Liu, J. & Diamond, J. Revolutionizing China's environmental protection. *Science* **319,** 37–38 (2009).

24. Tan, X. *et al. Scaling Up Low-Carbon Technology Deployment: Lessons from China* (World Resources Institute, 2011).
25. Ueno, T. *Technology Transfer to China to Address Climate Change Mitigation* (The Climate Policy Program, Resources for the Future, 2009).
26. Jacques, D. A., Guan, D., Geng, Y., Xue, B. & Wang, X. Inter-provincial clean development mechanism in China: A case study of the solar PV sector. *Energy Policy* **57,** 454–461 (2013).
27. Guan, D. & Hubacek, K. China can offer domestic emission cap-and-trade in post 2012. *Environ. Sci. Technol.* **44,** 5327 (2010).
28. Cui, L-B., Fan, Y., Zhu, L. & Bi, Q-H. How will the emissions trading scheme save cost for achieving China's 2020 carbon intensity reduction target? *Applied Energy* (in the press).
29. Hoekstra, R. & van den Bergh, J. C. J. M. Comparing structural and index decomposition analysis. *Energy Economics* **25,** 39–64 (2003).
30. Dietzenbacher, E. & Los, B. Structural decomposition techniques: Sense and sensitivity. *Econ. Syst. Res.* **10,** 307–323 (1998).
31. Ang, B. W. The LMDI approach to decomposition analysis: A practical guide. *Energy Policy* **33,** 867–871 (2005).
32. Hoekstra, R. & van den Bergh, J. C. J. M. Structural decomposition analysis of physical flows in the economy. *Environ. Res. Econ.* **23,** 357–378 (2002).
33. National Bureau of Statistics *China Energy Statistical Yearbook 2010* (China Statistics Press, 2011).
34. National Bureau of Statistics *China Energy Statistical Yearbook 2003* (China Statistics Press, 2004).
35. China Economic Census Office of the State Council *China Economic Census Yearbook 2008* (China Statistics Press, 2011).
36. Guan, D., Liu, Z., Geng, Y., Lindner, S. & Hubacek, K. The gigatonne gap in China's carbon dioxide inventories. *Nature Clim. Change* **2,** 672–675 (2012).
37. Guan, D., Hubacek, K., Weber, C. L., Peters, G. P. & Reiner, D. M. The drivers of Chinese CO_2 emissions from 1980 to 2030. *Glob. Environ. Change* **18,** 626–634 (2008).
38. Weber, C. L., Peters, P. G., Guan, D. & Hubacek, K. The contribution of Chinese exports to climate change. *Energy Policy* **36,** 3572–3577 (2008).
39. Liu, Z., Geng, Y., Lindner, S. & Guan, D. Uncovering China's greenhouse gas emission from regional and sectoral perspectives. *Energy* **45,** 1059–1068 (2012).
40. Lindner, S., Liu, Z., Guan, D., Geng, Y. & Li, X. CO_2 emissions from China's power sector at the provincial level: Consumption versus production perspectives. *Renew. Sust. Energy Rev.* **19,** 164–172 (2013).

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Author contributions
D.G., S.K. and K. Hubacek designed the research; D.G., Z.L. and Q.Z. compiled the data; D.G. and K. Hubacek performed initial decomposition analysis and produced early drafts; S.K. performed panel data analysis; all authors contributed to interpretation of the results and writing.

Additional information
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Competing financial interests
The authors declare no competing financial interests.