LETTERS
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Adaptation responses to climate change differ between global megacities

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Urban areas are increasingly at risk from climate change, with negative impacts predicted for human health, the economy and ecosystems[1,2]. These risks require responses from cities to improve their resilience. Policymakers need to understand current adaptation spend to plan comprehensively and effectively. Through the measurement of spend in the newly defined 'adaptation economy', we analyse current climate change adaptation efforts in ten megacities. In all cases, the adaptation economy remains a small part of the overall economy, representing a maximum of 0.33% of a city's gross domestic product (here referred to as GDPc). Differences in total spend are significant between cities in developed, emerging and developing countries, ranging from £15 million to £1,600 million. Comparing key subsectors, we demonstrate the differences in adaptation profiles. Developing cities have higher proportional spend on health and agriculture, whereas developed cities have higher spend on energy and water. Spend per capita and percentage of GDPc comparisons more clearly show disparities between cities. Developing country cities spend half the proportion of GDPc and significantly less per capita, suggesting that adaptation spend is driven by wealth rather than the number of vulnerable people. This indicates that current adaptation activities are insufficient in major population centres in developing and emerging economies.

Most of the world's population now lives in cities and that proportion is set to continue to rise[3]. There are many potential impacts of climate change on cities and urban areas that have been identified[1,4–9]. These include effects on human health, energy demand and availability of water, as well as the effects of sea-level rise on coastal cities and of extreme weather events on the built environment[5]. Cities in developing countries are thought to be even more vulnerable to climate change owing to widespread poverty[10,11], lack of infrastructure, unplanned informal settlements[12] and a lack of spending on adaptation[13]. There have been a number of studies on the potential effects of climate change on cities[5], but it is more difficult to analyse what is being done at present in response. Evidence suggests that although there is some planning for adaptation, there is a limited implementation; but this may be due to the fact that most studies have not assessed the processes of adaptation[14] over time[15]. This is perhaps due to a lack of potential data for analysis. The scale of economic response is one method of assessing what is being done at the city level in the process of adapting to climate change. It is vital to provide information to policymakers on what they are spending and how this is influencing a city's adaptive capacity. Comparing the scale of economic responses (and their composition) between cities can highlight whether resources are being allocated fairly or efficiently, where different cities may have different funding priorities for adaptation, and where further funding (from local, national or international organizations) is required. In this study, we define the adaptation economy as the total spend on the activities defined under the 'adaptation and resilience to climate change' sector, further details of which are in the Methods and Supplementary Information sections. As outlined in the Methods, this required the creation of a new classification of economic activities relating to 'adaptation and resilience', and then a specific subset of activities relating to adaptation and resilience to climate change.

Methods developed for the UK's Department of Environment, Food and Rural Affairs (Defra) and the Greater London Authority to measure adaptation and resilience have been extended and applied both globally and for specific chosen cities. The total global spend in 2014/15 on adaptation and resilience to climate change was £223 billion. It is therefore, a sizeable economic sector, but represents only 0.38% of global GDP. A high proportion of the population and economic activities at risk from climate change are located in urban areas, and the growth of large cities in developing countries has led to a growth in vulnerable communities in informal settlements, which are more exposed to extreme weather events[14]. Cities have to make social and political choices in the face of a group of urban issues (from health, to education, to the environment), which in each case includes a particular set of climate risk vulnerabilities. Cities are also home to the ever-increasing billions of people living in urban areas: are they doing enough?

Ten cities were chosen for this study on the basis of their size, geographical location and their developmental status. The cities are London, Paris, New York, Mexico City, São Paulo, Beijing, Mumbai, Jakarta, Lagos and Addis Ababa. Selection criteria for the cities can be found in the Methods. It is important to study a range of cities in different regions of the world, with different climates and at different states of socio-economic development. Although, in economic terms, disaster losses from weather, climate and geophysical events are greater in developed countries, fatalities and economic losses as a proportion of GDP are higher in developing countries[16].

Total spend on adaptation and resilience to climate change in 2014/15 (Fig. 1a) suggests that there are major differences in the adaptation responses between cities with different development profiles. The total spend ranges from £15 million to £1,600 million and tracks the financial resources of each city, which may suggest that adaptation spend is linked with protecting stocks of capital. Comparing the adaptation economy spend as a percentage of cities' GDP shows another pattern emerging (Fig. 1b). The developed country cities all spend ~0.22% GDPc on adaptation, whereas the developing country cities spend ~0.15% GDPc. The exception is Beijing, which spends the most at 0.33% GDPc. This difference

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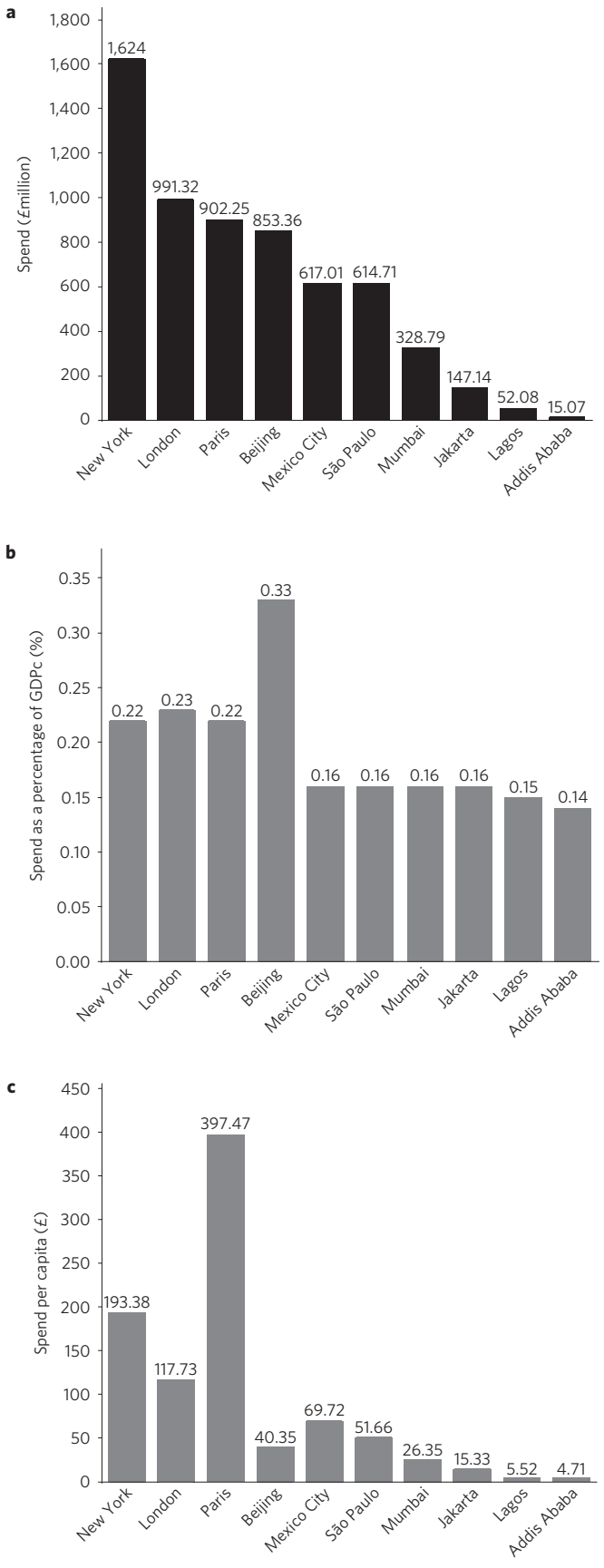

Figure 1 | Megacity spend on adaptation and resilience to climate change in 2014/15. a, Total spend (£million). **b**, Spend as a percentage of city's GDP (GDPc). **c**, Spend per capita (£).

in approach by developing country cities is significant given the large and rapidly growing population of these cities (the greatest urban population growth to 2050 will be in China, India, Nigeria and Indonesia[3]), and therefore the number of people vulnerable to future climate change risks. For example, proportionally the spend in Jakarta (the most populous city in Southeast Asia, with a population of 9.6 million[17]) is less than 50% of Beijing's. Beijing's higher spend compared with other cities of emerging and developing economies is notable. It is perhaps influenced by strong centralized policy frameworks in China. Since 2007, the Chinese government has developed a national policy framework that has included climate change adaptation in both urban and rural areas. With a determined central government campaign to position local governments as key actors for legislating for and responding to climate change, by 2010 all provinces had drawn up a climate change adaptation plan and have their own task forces[18].

It is worth considering the significance of the spend in the adaptation economy in relation to the size of the city's population. Figure 1c shows the vast differences in spend per capita. Even taking into account the small population of Paris' city proper, the range from £4.71 per capita for Addis Ababa to £193.38 per capita for New York is significant. These figures demonstrate that in absolute, proportional and per capita terms (variations in purchasing power, and access to technology and resources notwithstanding), there are large differences in the scale of adaptation responses between these different cities. Although cities in developing countries certainly have greater competing needs for their budgets, this puts further weight behind the suggestion that adaptation responses track capital to be protected rather than people to be protected.

Figure 2 shows the breakdown of how the money is allocated to climate change adaptation. In the developing and emerging cities (apart from Beijing), greater proportions of the adaptation economy are derived from the 'agriculture and forestry' and 'natural environment' subsectors. In addition, Addis Ababa and Lagos also have higher proportional spends on the 'health' subsector, whereas Beijing, London, New York and Paris spend more proportionally on 'energy', 'water' and 'professional services'. One exception is the relatively high proportion of professional services in Addis Ababa, which we suggest may be due to the sensitivity of the percentages due to the very low total spend on the adaptation economy in that city. The 'built environment' subsector is an interesting comparison as percentages are fairly similar between developed and developing economies, apart from Beijing; where it is nearly 50% of the spend on adaptation to climate change. Beijing also has the lowest proportional spend on the natural environment and, perhaps surprisingly, the 'information and communication technologies' (ICT) subsectors. The greater spend on agriculture and forestry, the natural environment and in some cases health demonstrates the very different profile of needs in developing country cities compared with established global financial centres, where professional services, built environment, energy and water dominate. The last two perhaps are significant in providing high-consumption, high-comfort lifestyles in developed megacities.

Given the differences in sectoral breakdown, the vast gap in overall spend on adaptation and resilience to climate change and the differences in proportional spend, there are perhaps some suggestions that megacities in developing and emerging economies do not have sufficient resources at present to adequately deliver adaptation for their current and future populations. This is especially cause for concern when the projected future populations of cities such as Jakarta or Lagos are taken into consideration.

One of the most important subsectors is likely to be 'disaster preparedness in relation to climate change', and it is very clear that spend in this subsector is considerably lower in cities

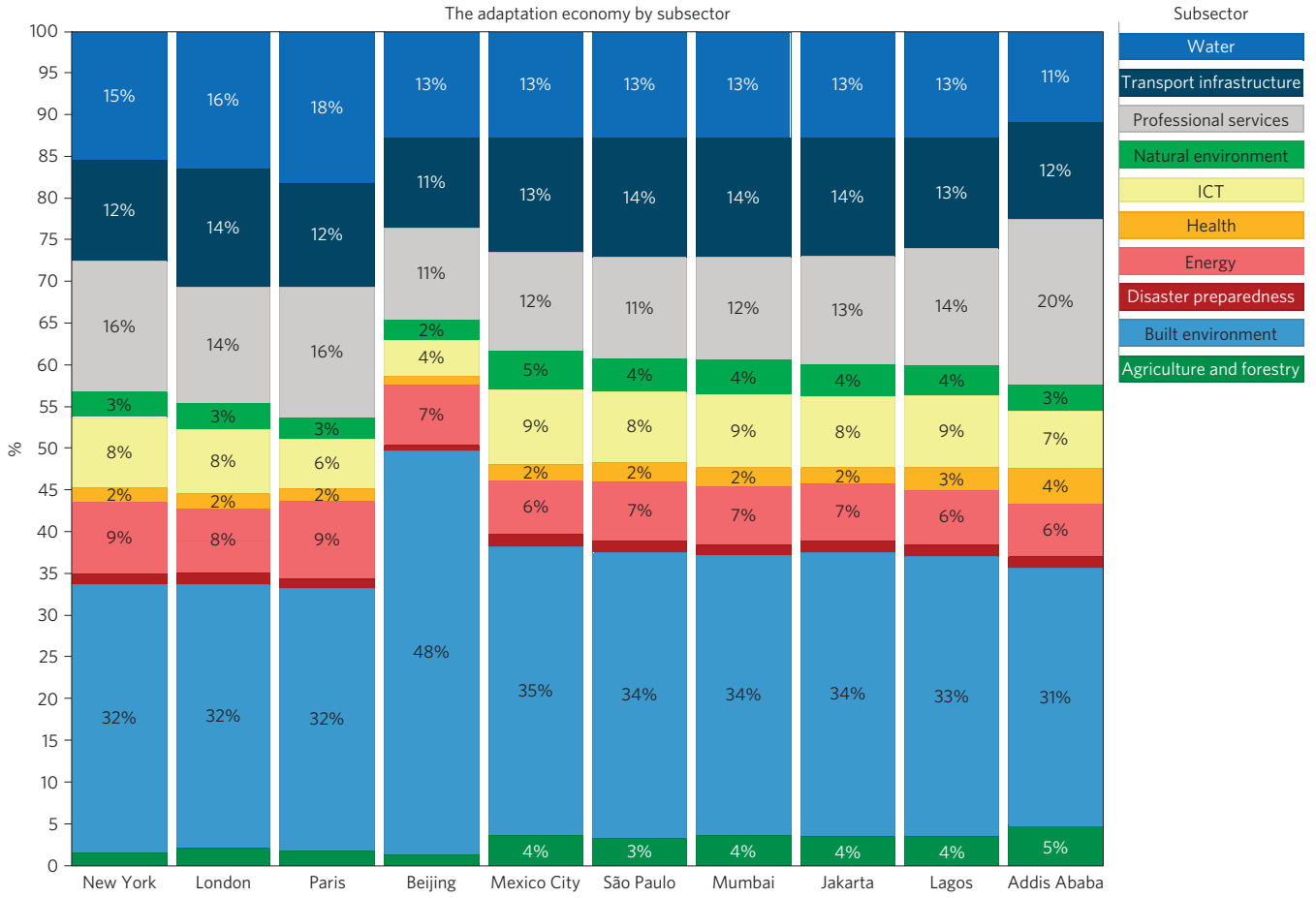

Figure 2 | Breakdown of spend on adaptation and resilience to climate change in 2014/15 by subsector (%).

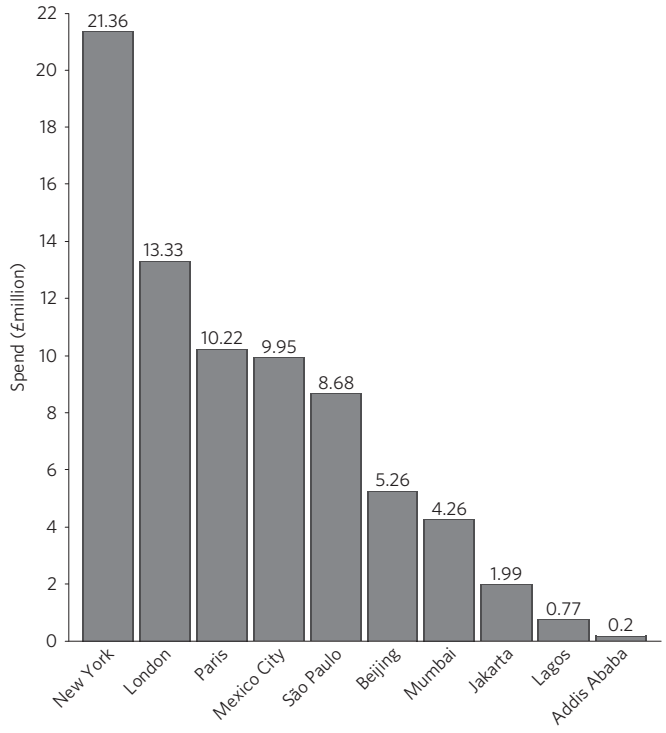

Figure 3 | Spend on disaster preparedness in relation to climate change for 2014/15 (£million).

in developing countries. This sector includes a range of activities from financial instruments, to advanced risk modelling, to drainage systems and coastal defences. Figure 2 shows that, proportionally, the amount spent in each city is similar. However, as illustrated in Fig. 3, in absolute terms of financial spend the difference is staggering. In Addis Ababa, a city of approximately 3.2 million people (2014 projection)[19], just £0.2 m was spent on economic activities related to disaster preparedness in relation to climate change. As further illustration, in this subsector New York spent £0.87 m on engineering consulting services for sustainable urban drainage systems, whereas Addis Ababa spent just £0.01 m.

From our research, we can see that there are different profiles emerging, which could match the categories of cities in developing, emerging and developed countries. As shown however, Beijing seems to have a unique profile, with a higher adaptation economy spend on the built environment and a much lower proportional spend on the natural environment. Much of the existing adaptation economy activity seems to have evolved around existing policy focus areas and specialisms at the city level. Some specialist activities have evolved naturally, and are likely to continue to do so. These differences demonstrate in part the more urgent focus in developing countries on providing a base level of services for their citizens such as protecting health, agriculture and forestry. In contrast, in developed countries, the financial and professional services sectors contribute a higher proportion of the cities' GDPc and attract a greater proportion of the spend from the adaptation economy budget.

Despite the large differences in spend on the adaptation economy, there is clear commitment in most cities, with strong

Table 1 | Growth in the adaptation economy between 2008/09 and 2014/15.

City	Spend (£million)	Annual growth (%)						Spend (£million)	2008/09–2014/15 average
	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15	2014/15	annual growth (%)
New York	1,275.50	3.15	3.41	3.71	4.27	5.62	4.53	1,624.39	4.11
London	786.31	3.07	3.38	3.54	4.20	5.30	4.14	991.32	3.94
Paris	712.03	3.09	3.34	3.69	6.68	2.89	4.51	902.25	4.03
Beijing	665.97	3.00	3.34	3.60	5.53	5.38	4.50	853.36	4.22
Mexico City	493.53	3.11	3.37	3.64	4.21	3.06	5.37	617.01	3.79
São Paulo	485.23	3.08	3.36	3.72	5.63	3.54	8.53	614.71	4.02
Mumbai	264.36	3.12	3.36	3.69	2.62	3.56	5.90	328.79	3.70
Jakarta	114.93	3.28	3.34	3.73	5.06	3.81	6.02	147.14	4.20
Lagos	44.42	2.88	3.50	3.70	−5.76	5.44	6.85	52.08	2.69
Addis Ababa	15.18	2.83	3.84	4.07	−25.78	9.74	9.68	15.07	−0.12

growth occurring over the past 7 years (Table 1). The sector remains volatile in less developed cities; in 2012/13 support for large adaptation programmes ended in Addis Ababa and Lagos (see Table 1). There are, however, encouraging signs, with strong growth in recent years in most developed and developing cities. The lower average annual growth figures for Addis Ababa and Lagos, and greater dependence on individual funding projects in these cities, suggests that a continued focus on climate change adaptation for developing countries and at-risk populations will be important.

The policy attention given to adaptation to climate change is relatively recent but despite this there is evidence that the adaptation economy has managed to maintain a significant and stable level of growth throughout the global recession in most cities. Recognizing that spend on climate change adaptation activities is likely to be a social and political choice, as such funds cannot be spent on other uses, this suggests that most governments managed to maintain a generally healthy economic environment for these activities in a difficult economic climate. The adaptation economy, defined as adaptation and resilience to climate change activities, is still a small part of the global economy, but its political and environmental importance is likely to rise. The adaptation economy is difficult to define, and thus to measure. It is likely to change in character rapidly as new activities are identified; however, this lack of defined identity does offer opportunities for cities and urban areas to develop specialisms and competitive advantages. The increasing awareness of the vulnerabilities of growing cities to extreme weather as a result of a changing climate may contribute momentum to the city-based development of new adaptation economy activities. We suggest that this methodology provides information and feedback to policymakers regarding the development of the economic responses to the challenge of adapting to climate change, where no such data have previously been available. As the importance of adaptation for global megacities continues to grow, the availability of such information will be of vital importance to policymakers. Further research will be required to examine each city's adaptation response in greater detail and develop more detailed policy advice on a case-by-case basis.

The differences in spend on adaptation to climate change between the cities in the study as a percentage of GDPc and on a per capita basis do show some cause for concern. Mexico City, São Paulo, Mumbai, Jakarta, Lagos and Addis Ababa all spend less than half as much as Beijing as a percentage of GDPc. Jakarta, Lagos and Addis Ababa spend less than one-tenth per capita, compared with New York. These cities face much greater competing needs for expenditure, but the evidence seems to suggest that current adaptation responses may be largely influenced by market-based responses to protecting physical capital, rather than at-risk populations. In particular, spend on disaster preparedness in relation to climate change, for example, is very low in cities that, owing to present and future population pressures and their geographical locations, are likely to be vulnerable to a range of climate change risks. International organizations, as well as national governments, must: ensure that climate change adaptation remains a priority, continue to provide policy support for growth in economic sectors relating to climate change adaptation and ensure that adequate and consistent funding is available to cities in developing and emerging economies.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions
L.G. and M.M. conceived and wrote the paper, M.P. and S.H. provided the unique data and contributed to the analysis and interpretations.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to L.G.

Competing financial interests
The authors declare no competing financial interests.

Methods

Cities for this study were selected on the following criteria: recognized status as a megacity (population greater than 3 million or GDP in the top 25 of cities, or both), any type of membership to the C40 group of Cities for Climate Leadership, and geographical location. A range of cities was chosen to represent most major world regions and population centres (North, Central and South America, Europe, South, Southeast and East Asia, and Sub-Saharan and East Africa). The cities in this study also cover most different strata of classifications of development status. Examples considered include: the FTSE Annual Country Classification (Developed, Advanced Emerging, Secondary Emerging, Frontier, Unclassified/Developing[20]), the UN classification used in World Economic Situation and Prospects (developing economies, economies in transition and developed economies[21]) and the World Bank's Income Classification (low, lower–middle, upper–middle and high income economies[22]). Population estimates for the 'city proper' in each case were taken from official sources at the municipal or national level[17,19,23–30]. This definition means that the population of the city of Paris is considerably smaller than the Île-de-France city region; this is much more pronounced than the other cities in the study and does lead to a skewing of the Parisian data. However, we have found that other attempts to define metropolitan regions, city regions or metro areas create greater definitional and comparability issues.

The adaptation economy data set, as developed by kMatrix in partnership with numerous stakeholders (including contributors from Greater London Authority, Ricardo-AEA, Imperial College London, Defra, Climate Change Committee, Triple E Consulting, London School of Economics), includes the key adaptation measures identified by the Intergovernmental Panel on Climate Change in Part A of the Contribution of Working Group II (ref. 31). The classification builds on attempts by the UK Department of Environment, Food and Rural Affairs to measure adaptation and resilience in 2009/2010. The definition for adaptation and resilience was extended by the Greater London Authority in 2014 to measure a wider range of economic activities to measure the adaptation economy for London, and to compare London's economic activity with other UK and International cities, with a focus on urban adaptation activities (kMatrix, *The Adaptation Economy 2012/13*, manuscript in preparation).

As per the above, a new definition of adaptation and resilience to climate change was developed. Then the process began with the creation of the top-down taxonomy of the entire 'make and mend' economy, and then adaptation and resilience in all forms. Then these categories were filtered to isolate economic activities that can be strictly identified as being relevant to adaptation and resilience to climate change. The specific activities of adaptation and resilience to climate change are drawn from ten sectors of the economy at large: agriculture and forestry, built environment, disaster preparedness, energy, health, ICT, natural environment, professional services, transport infrastructure, water (see Supplementary Information for further detail of the subsectors; in each one, only the activities related to adaptation and resilience to climate change are reported). Examples of the specific activities measured under these sectors include: climate change-related inland waterways defence management, development and manufacture of advanced water management technologies and R&D in forest management techniques for climate change adaptation.

The methodology used for data acquisition and analysis is based on a system originally developed at Harvard for triangulating transactional and operational business data to estimate economic values in areas where government statistics and standard industry classifications are not available[32]. The new taxonomy was populated from the bottom up, searching for evidence for the ideal definition and including only elements where the evidence is available.

kMatrix has, over the past 20 years, compiled over 27,000 independent databases and sources to cover most global financial transactions. Each database or source is coded so that sector- and region-specific questions can be addressed. For this study, a subset of 1,100 relevant data sources was selected. The large number of data sources is essential, as each transaction has to be triangulated both with multiple sources, and different types of measurement (sales, insurance value, and so on), to ensure its accuracy. For each transaction listed in the adaptation economy data, a minimum of seven separate sources must independently record the transaction for it to be confirmed and included in our database. These databases have been tracked and verified over a number of years. Using multiple sources of data and multiple types of data makes it possible to arrive at accurate estimates of transactional value that are not possible using a single source. Moreover, city-level data can be unreliable, especially under certain political contexts if provided by the cities themselves; hence, the triangulation of data from multiple sources avoids such biases.

For the adaptation economy, data are produced to a confidence level of between 80% and 88%. Confidence levels are a function of the range of source values assembled for each data point. Each final data point is the mean of the final range of values (after outliers are removed). The confidence level is the difference between the mean value and the most extreme values in the range. An 85% confidence level means that the difference between the mean and the extreme values is 15%. This same methodology has also been used to track the emergence of the carbon market intelligence sectors[33], and by the UK Department for Business, Innovation and Skills for reporting on the Low Carbon and Environmental Goods and Services sector[34].

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