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Transnational municipal networks and climate change adaptation: A study of 377 cities

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ABSTRACT

Cities have increasingly recognised the risks posed by climate change and the need to adapt. To support climate action, cities have formed cooperative networks such as the C40 Cities Climate Leadership Group, the Global Covenant of Mayors and the International Council for Local Environmental Initiatives. However, a lack of scientific evidence exists when it comes to the actual impact of network participation, especially in the context of adaptation. This study is the first to test statistically the association between network membership and progress in adaptation planning in 377 cities globally. The results show that network members are more likely to have started the adaptation process than other cities, and that being a member of multiple networks is associated with higher levels of adaptation planning. Moreover, cities in wealthier countries are more likely to be more advanced in adaptation planning than others. We consider the possible explanations for these results based on the previous literature and information gathered from the networks. The main implications of our study are that network organisations should consider how to encourage the adaptation process among their members and the increased involvement of cities from lower-income countries.

1. Introduction

Cities are important actors in climate change adaptation (Revi et al., 2014; van der Heijden, 2018; van der Heijden et al., 2018). High hopes have been expressed about the benefits of networking between cities for climate action. With the support from inter-city networks such as the C40 Cities Climate Leadership Group (C40), the International Council for Local Environmental Initiatives (ICLEI) and the Global Covenant of Mayors (GCoM), cities are pictured as leading the way to a climate-safe future, combining ambitious mitigation and adaptation efforts (C40, Solecki et al., 2018; van der Heijden et al., 2019). Cities are also seen as the drivers of globally sustainable development (UNEP, 2011; Barber, 2017; ICLEI, 2018; Solecki et al., 2018; van der Heijden et al., 2019).

Meanwhile, the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (FAR) states that there is medium confidence, based on medium evidence and with medium agreement, that horizontal learning through networks of cities benefits urban adaptation (Revi et al., 2014: 539). Despite the enthusiasm surrounding these networks, there is little systematic evidence concerning the effects of network participation (Wolfram et al., 2019). There has been no research to show whether network participation is associated with progress in planning of climate change policies at the city level, especially when it comes to adaptation (Fünfgeld, 2015; Woodruff, 2018).

We define transnational municipal networks (TMNs) related to climate change as organisations that aim to support cooperation between cities to improve their climate change mitigation and adaptation work. TMNs can require cities to adopt certain quantitative or qualitative climate goals. They organise events, produce information (e.g. reports on their members' climate actions), offer tools and/or resources and represent cities internationally. TMNs originally concentrated on mitigation, but adaptation has increasingly been on their agenda. Although some scholars have begun to

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study their role in adaptation, it remains understudied (Juhola and Westerhoff, 2011; Busch, 2015; Woodruff, 2018). The big question regarding adaptation is whether these networks live up to the high expectations to increase local adaptation efforts (Woodruff, 2018).

To our knowledge, this study is the first effort to answer this question through a statistical analysis of a global sample of cities. We analysed the connection between TMN membership and progress in climate adaptation planning worldwide using the Adaptation Process Index (API), which is the first global measure of city-level climate change adaptation planning efforts, developed by Araos et al. (2016b). We have employed their data set in this study, analysing the connection between memberships in three key global TMNs—C40, ICLEI and GCoM—and the progress of cities in their adaptation planning processes.

The study covers 377 large cities (at least one million inhabitants) for which the API is currently available (Araos et al., 2016b). Large cities are of interest in climate adaptation research due to their economic importance and the risks related to population concentration (Hunt and Watkiss, 2011). Moreover, earlier studies have found that large cities seem to be drivers in TMNs (Woodruff, 2018).

Previous empirical studies have predominantly focused on a handful of cities in wealthy western countries (van der Heijden, 2018), in the form of case studies of individual cities or limited geographical areas (Kern and Bulkeley, 2009). The samples of the few earlier large-N studies have either been from Europe (Reckien et al., 2018) or from North America (Woodruff, 2018). The existing studies also reflect differences in focus. Reckien et al. (2018) reported on the status and drivers of European city-level climate change mitigation and adaptation planning in relationship to national- and international-level planning and legislation. Woodruff (2018) analysed how factors like planning capacity affect the probability of a city to join TMNs.

This study goes beyond the existing qualitative literature by statistically testing the association between TMN participation and climate adaptation – not just showing how some cities may benefit from these networks but testing whether this is the case at the aggregate level and by seeing what kind of cities are more likely to benefit than others. We also go beyond the limited existing quantitative work by analysing a global sample which includes a significant number of non-western cities, especially from China and India. This approach provides new insights into the global role of TMNs by significantly widening the geographical scope of the analysis compared to earlier studies.

We selected three TMNs[1] to analyse: C40, ICLEI, and GCoM (formerly the Covenant of Mayors and the Compact of Mayors). C40 is a network of global mega-cities concentrating especially on climate action. GCoM also concentrates on climate issues. ICLEI has a broader aim to support the sustainability of cities, but it also strongly promotes climate action, and adaptation was included in its strategic plan for 2006.[2] These networks have been identified as important global climate change-related TMNs in previous studies (Kern and Bulkeley, 2009; Heidrich et al., 2016; Busch, 2015; Busch et al., 2018; Woodruff, 2018; Reckien et al., 2018; van der Heijden et al., 2019).

The C40 was established in London in 2005. Its target is to develop and implement policies and programmes that generate measurable reductions in both greenhouse gas emissions and climate risks. The network promotes cities as leaders of change, and cities need to pass an application process to become members (www.c40.org). According to Davidson and Gleeson (2015), C40 represents a new strategic urbanism phase of transnational urban governance, because it ties together the most influential and economically-powerful mayors of global mega-cities to adopt a more visible political stance. C40 also has several private sector partners, like Bloomberg Philanthropies (https://www.c40.org/partners).

ICLEI is the oldest of the three networks, founded in 1990. When compared with the C40, the climate agenda of ICLEI is more diverse, targeting also smaller urban areas and connecting the work in general themes of sustainability. It has an annual membership fee (depending on the region, population and per capita gross national income), but membership is open to all cities and regions (www.iclei.org).

GCoM differs from the other two. It is a combination of initiatives, including Covenant of Mayors (launched 2008), Compact of Mayors (launched 2014) and Mayors Adapt (launched 2014). These were combined in 2015. GCoM aims to give political support to the climate work of the cities by supporting the engagement of mayors. According to them, they are world's largest global alliance for city climate leadership with over 9000 members (https://www.globalcovenantofmayors.org/about/).

Although these networks operate independently, they have interconnections. C40 and ICLEI had a role in creating the Compact of Mayors, and they also work together on a range of projects, like mitigation related Carbon Disclosure Project.

Next, we review the existing literature related to the impact of TMNs, and draw our hypotheses, before describing our dataset and the methods. In the results section, we have presented the average and median APIs for cities with different combinations of network memberships, as well as the results of statistical analysis. Our findings indicate that there is a statistically significant connection between network participation and starting the adaptation process, and that being a member of multiple networks is associated with higher levels of adaptation planning. Finally, we discuss this in light of the existing literature, and draw a conclusion.

2. Literature review and hypotheses

The role of TMNs has been studied mostly from the point of view of mitigation (Fünfgeld, 2015). We provide a short overview of recongnized benefits in Table 1. The benefits are often connected to information sharing, learning, shaping mitigation initiatives, and increased resources. It has been found that networks help municipalities to act when state-level action is lacking, and that they act as city advocates shaping the political environment and legal frame. Networks may cause similar effects when it comes to adaptation (Castán Broto and Bulkeley, 2013).

Overall, we identify two specific topics in this discussion on which we wish to shed light. First, claims have been made that networking cities are pioneers of mitigation (Kern and Bulkeley, 2009), and the same may apply when it comes to adaptation. Relatively strong claims state that networks do support local climate adaptation (Revi et al., 2014; Woodruff, 2018), even though little empirical evidence exists showing that networks have an effect on actual city-level climate action. Proving this claim is difficult, and scholars should be critical of highly normative claims on the impact of networks (van der Heijden, 2018). If city networks do support local climate change adaptation, it would be reasonable to expect members would have a higher API. Hence, we hypothesise that

H1. *Network members are more advanced in their climate change adaptation planning processes than non-members.*

[1] We decided to leave 100 Resilient Cities out since it was founded 2013 and it concentrates on resilience, a different concept than adaptation. Also, their future plans are unclear: http://www.100resilientcities.org/closing-note/.

[2] http://archive.iclei.org/index.php?id=10832.

Table 1
Overview of benefits of networking. MLG = multi-level governance, SNA = Social Network Analysis.

Author(s):	Year:	Method(s):	Scope:	Main results concerning (potential) network benefits:
Bulkeley et al.	2003	theoretical	TMNs as part of MLG in Europe	preliminarily: lobbying, information sharing, learning, policy initiative creation
Kern & Bulkeley	2009	case study	TMNs as part of MLG in Europe	pioneers benefit: information sharing, learning, access to funding, legitimacy
Andonova et al.	2009	theoretical	networks as transnational governance	information sharing/diffusion, learning, possibly increased resources
Lee & van de Meene	2012	SNA	learning in C40	learning, information sharing
Busch	2015	case study	Influence of TMNs in German cities	information sharing, learning, goal setting, city advocate
Lee & Koski	2015	statistical methods	mitigation in C40 member cities	motivation of local policy & action, spills over to non-members
Busch et al.	2018	survey, interviews	Influence of TMNs in German cities	information sharing, learning, possibly increased resources

Many cities are members of more than one network. It is possible that different networks offer different kinds of support, making it reasonable to use resources in multiple memberships. If networks do support climate change adaptation, it would be logical to assume that the more networks a city participates in, the more support it gets. Hence, we hypothesise that

H2. *The more networks a city is a member of, the more advanced it is in its adaptation planning process.*

Second, TMNs seem to be biased towards the wealthy western countries. When studying mitigation networks, Bansard et al. (2017) found that cities in Europe and North America are over-represented, and the cities which participate in several networks connecting them together come from this region. Cities in wealthier countries seem to end up at the core of networks defining best practices, which may exclude the cities in less wealthy countries and increase differences between cities (Kern and Bulkeley, 2009; Shi et al., 2016). This is because cities in wealthy countries tend to have higher overall administrative capacities to design policies, as well as higher capacities to implement adaptation and mitigation measures. For example, C40 may seem horizontal, but it is still largely dominated by cities like New York and London (Acuto, 2013, see also Bouteligier, 2013; Lee, 2018).

Cities with lower capacities may adopt passive roles, with their membership becoming mostly symbolic (Kern and Bulkeley, 2009). Not all members have access to the benefits offered by the networks (Lee, 2015; van der Heijden, 2018), and although networks have been active for some decades now, a great number of cities have not joined (van der Heijden, 2018). On the other hand, it has been argued that cities lagging in climate action reap the greatest benefits from the networks (Busch et al., 2018; Reckien et al., 2018). Therefore, we test the hypothesis

H3. *The wealthier the country in which a city is located, the more advanced the city is in its adaptation planning process.*

Our dataset is the first global, large-N sample of city-level climate adaptation measures. With these data, we can not only test H3, but also control for wealth differences when testing H1 and H2. Further, we can assess whether our two key independent variables, network participation and wealth, are correlated.

3. Material and methods

We used data on 997 adaptation initiatives in 402 urban areas around the world (Araos et al. (2016a, b). The dataset includes information about public adaptation planning in urban areas[3] with more than one million people. The researchers considered material in the following 13 languages, with a minimum of four cities per language: English, Spanish, French, Chinese, Arabic, Russian, German, Portuguese, Farsi, Korean, Japanese, Turkish, and Indonesian (Araos et al., 2016b).

Araos et al. (2016b) collected the data from climate change planning documents in a web-based search using the Google search engine. The search terms were “climate change” and the city’s name. Thus, the search focussed on “highly intentional” adaptation policies as defined by Dupuis and Biesbroek (2013: p. 1480). The data was collected between January 2 and March 29, 2014 (Araos et al., 2016b). This method is consistent with other studies collecting information about adaptation planning (Reckien et al., 2014, 2018; Lesnikowski et al., 2016).

3.1. Variables

Our dependent variable is the adaptation process index (API, Araos et al., 2016b), drawn from the data described above. The index includes the following criteria: presence of climate projections, presence of vulnerability assessments, consideration of multiple sectors, reassessment of development priorities in the face of climate change, availability of climate change planning documents, consultations and stakeholder engagement, management of barriers and uncertainty, and monitoring and evaluation of adaptation activities. The more criteria a city fulfilled, the higher its API. The values range from 0 to 8. For further theoretical justifications on why these particular criteria are included in the API, see (Araos et al., 2016b).

The main independent variable of interest is network participation. For each city in the dataset, we coded whether it is (or is not) a member of a network on spring 2019, and if it is a member, whether the city joined the network before 2014. We received the information about memberships and when the cities joined through personal communication with the networks, and through webpage searches when necessary. Due to some missing data, we had to drop some cities out of the analyses leaving us with 377 cities. We use network participation to explain the variation in API in two ways: first, by using each network membership as an independent variable separately, and then by combining network memberships into one variable that measures the number of networks of which the city is a member.

As national-level control variables, we used location at the continent level (Africa being the reference category), level of national adaptation legislation at the time based on Climate Change Laws of the World database, 2017 (0 = no legislation, 1 = executive 2 = legislative) and gross domestic product. As a city level control variable, we used the size of the city. We controlled for location and GDP because earlier research found TNMs to be biased towards wealthy countries in Europe and North America and cities in wealthy countries have better resources for climate action, as explained in section 2. We controlled for the existence of national legislation because cities in countries in which legislation requires cities to plan for adaptation are likely to be more advanced in their adaptation planning, and for city size, because larger cities may have better capacities for adaptation than smaller ones (cf. Reckien

[3] The terms “city” and “urban area” do not necessarily refer to areas defined by administrative boundaries, but the data collection is based on the United Nations’ definition of “urban agglomeration”.

Table 2
Variables used in the analyses.

Continuous variable information	Minimum	Maximum	Mean	Std. Deviation
Adaptation process index	0	8	1.58	2.47
GDP 2016 (in thousands)	0.80	87.86	22.54	18.19
Population (100 000)	10.02	369.33	31.14	37.91
Categorical variable information	N	Percent		
Memberships:				
C40 member (total)	74	19.89		
C40 member 2014 or later	32	8.49		
C40 member before 2014	42	11.14		
ICLEI member (total)	110	29.18		
ICLEI member 2014 or later	25	6.63		
ICLEI member before 2014	85	22.55		
GCoM member (total)	150	39.79		
GCoM member 2014 or later	127	33.69		
GCoM member before 2014	23	6.10		
Member of 1 network before 2014	85	22.55		
Member of 2 networks before 2014	28	7.43		
Member of 3 networks before 2014	3	0.80		
Level of adaptation legislation:				
Executive	212	56.23		
Legislative	47	12.47		
Continent:				
Africa	46	12.20		
Asia	185	49.07		
Europe	34	9.02		
Latin America	56	14.85		
North America	50	13.26		
Oceania	6	1.59		

et al., 2018).

Table 2 presents descriptive statistics of all variables used in the analyses. Of the sample of 377 large cities, 202 were members of at least one network, which is more than half of the sample. Out of these 202 cities, 116 had joined at least one network before 2014 (30.77% of the whole sample and 57.43% of the network members). Overall, the GCoM has the most members among the cities in our sample with 150 members, 110 cities in our sample are members of ICLEI and 74 are members of C40. The mean API score of the whole sample is very low, only 1.58 on the scale from 0 to 8.

3.2. Models

To test binary relationships between network participation and country-level GDP and API, we first used one-way analysis of variance (Raykov and Markoulides, 2013). We then analysed the relationship further by using zero-inflated negative binomial regression models. We used this model type to take into account the type and distribution of the dependent variable, the city's API.[4]

The API can only take non-negative integer values that arise from counting rather than ranking (Araos et al., 2016b). This kind of count data is typically analysed using Poisson regression models (Greene, 1994). However, the distribution of API across the cities analysed is overdispersed and contains excessive zeros, which creates a violation of the assumptions of a conventional Poisson model. The zero-inflated negative binomial model takes the large number of zeros into account and allows for the variance of the dependent variable to be greater than the mean, which is not the case in traditional Poisson regression models for count data (Greene, 1994).

Zero-inflated count regression models are a mixture of a generalized linear model for the dichotomous outcome, and a conventional event-count generalized linear model, such as negative binomial regression (Desmarais and Harden, 2013). This is why a zero-inflated negative binomial model divides the analysis into two distinct parts, a zero-inflation model and a count model (Greene, 1994). This means that two different processes are analysed at once, one analysing the probability of the dependent variable getting a value zero (a reversed binomial model), and the other analysing the distribution of the count variable including zero (Greene, 1994). In case of the API, the two processes are whether a city has started the adaptation process in the first place, and if so, how far along in the process it is. The expected value of the API is thus expressed as a combination of both processes:

$$\mu_i = \pi_i * 0 + (1 - \pi_i) * \exp\left(x_i^T \beta\right),$$

where π_i is the probability that a city has not started the adaptation process and x_i is the count component of the model (Zeileis et al., 2008). We conducted the analysis using the pscl package in an R environment for statistical computing.

The API includes two parts describing the awareness of vulnerability and exposure: vulnerability and climate trend (Araos et al., 2016b). It is not probable that vulnerability and/or exposure that a city is unaware of will affect the adaptation planning process. We did not include vulnerability as an explicit control variable, because there is no reliable global index which would describe vulnerability at the city level before 2014 (Araos et al., 2016b) and vulnerability is partly covered by controlling for economic capacity, since existing patterns of development have profound effects on vulnerability (Shi et al., 2016).

4. Results

Our first and second hypotheses are that network members have higher APIs than other cities and that the more memberships, the higher the API. Results of the analysis of variance showed a

[4] We also conducted the analyses using multilevel negative binomial regression but ended up with the single level model because the model estimate for country level variance was 0. This might be due to the fact that more than half of the cities in our data are the only observation from their country.

Table 3
Comparing means of API and GDP by network participation.

	API			GDP (in thousands)		
	Mean	95% confidence interval		Mean	95% confidence interval	
		Lower	Upper		Lower	Upper
No network memberships before 2014	0.89	0.68	1.10	18.80	16.84	20.77
Member of 1 network before 2014	2.21	1.62	2.79	29.24	24.83	33.64
Member of 2 networks before 2014	5.21	4.12	6.31	34.86	27.86	41.85
Member of 3 networks before 2014	4.33	−5.71	14.37	43.02	27.44	58.60
ANOVA	F	Sig.		F	Sig.	
Between groups	41.051	0.000		14.461	0.000	
		95% confidence interval			95% confidence interval	
	Mean	Lower	Upper	Mean	Lower	Upper
Not a member of C40	1.14	0.91	1.37	21.56	19.58	23.54
Member of C40 before 2014	4.09	3.17	5.02	33.70	27.24	40.16
Member of C40 2014 or after	1.69	0.81	2.57	17.15	11.49	22.82
ANOVA	F	Sig.		F	Sig.	
Between groups	3.,527	0.000		10.223	0.000	
		95% confidence interval			95% confidence interval	
	Mean	Lower	Upper	Mean	Lower	Upper
Not a member of ICLEI	1.23	0.98	1.48	21.12	18.99	23.25
Member of ICLEI before 2014	2.64	1.99	3.29	28.35	24.21	32.48
Member of ICLEI 2014 or after	0.76	0.05	1.47	17.97	11.08	24.86
ANOVA	F	Sig.		F	Sig.	
Between groups	13.169	0.000		6.094	0.002	
		95% confidence interval			95% confidence interval	
	Mean	Lower	Upper	Mean	Lower	Upper
Not a member of CoM	1.01	0.77	1.25	16.77	14.98	18.56
Member of GCoM before 2014	5.22	3,98	6.45	43.45	39.04	47.86
Member of GCoM 2014 or after	1.78	1.33	2.24	29.07	25.35	32.79
ANOVA	F	Sig.		F	Sig.	
Between groups	39.082	0.000		42.496	0.000	

connection between network membership and adaptation planning progress, giving preliminary support to both hypotheses 1 and 2.

Table 3 presents the means and analysis of variance in API for the cities with different network membership combinations.[5] The numbers show that there is a connection between network memberships and higher APIs, especially when the city is member of two or three networks, or when it is member in C40 or GCoM. Our third hypothesis is that wealthier cities have higher APIs regardless of network participation, so we also analysed the correlation between API and GDP. Our results indicate a significant association between these two variables with a Pearson correlation of 0.339 ($p < 0.000$) between API and GDP.

Table 3 also presents the results from analysis of variance in GDP for cities with different network membership combinations. Cities that are not members of any of these networks have a significantly lower GDP compared to other cities. Specifically, members of GCoM and C40 have a higher GDP than non-members, but also members of ICLEI that joined before 2014 have a statistically significantly higher mean GDP compared to cities that are not members.

These analyses offer preliminary support to all three hypotheses. Wealth is connected to both network membership and the adaptation planning progress. However, differences in GDP between network members and non-members raise a question of whether these connections are independent or not. The results from zero-inflated negative binominal models give us a more detailed picture (Table 4).

Table 4 presents the results of the zero-inflated negative binomial models (models 0 to 6). They also support our hypotheses. Network members have been more likely to start their climate change adaptation planning process than other cities (H1), and being a member of multiple networks is connected to having a higher API (H2). These results hold when wealth, geographical location and legislation are controlled for. Also, cities in wealthy countries have higher API scores when network memberships are controlled for (H3). We also conducted the analyses using standard negative binomial regression as a robustness check. However, according to the Vuong test (Vuong, 1989) results, the zero-inflated model is a significant improvement over the standard negative binomial model (see supplement 2 and 3 for details).

The upper part of Table 4 shows the count part of the zero-inflated regression models, which are to be read like regular count regression models, i.e. a one unit increase in an independent variable results in exp(B) increase in the dependent variable. The lower part of the table shows the zero-inflation model, which indicates the probability of the dependent variable (API) being a certain zero. This indicates that the coefficient −1.87 for C40 members in Model 3 means that being a member of C40 decreases the odds of having an API value of zero by exp (−1.87) compared to other cities.

We began regression modelling by estimating a null model that includes only control variables, namely population, legislation, and continent. Model 0 shows that indeed, there are differences in the API of cities by continent. Asian and Latin American cities have significantly lower total APIs compared to the African cities in our sample (Model 0, count model), and all but Asian cities have a

[5] We analysed the means of API separately for cities with API >0. The results point to similar direction. For details, please see the supplement.

Table 4
Parameter estimates and model fit for zero-inflated negative binomial models explaining adaptation process index.

	Parameter estimates: count model	Model 0	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
	Intercept	1.82 (0.23) ***	1.78 (0.23) ***	1.82 (0.24) ***	1.78 (0.23) ***	1.92 (0.25) ***	1.95 (0.25) ***	1.83 (0.24) ***
H1	C40 member before 2014			0.23 (0.14)			0.20 (0.14)	
	C40 member 2014 or after			−0.03 (0.17)			−0.03 (0.18)	
	ICLEI member before 2014				0.03 (0.10)		−0.03 (0.10)	
	ICLEI member 2014 or after				−0.07 (0.28)		−0.05 (0.30)	
	GCOM member before 2014					0.62 (0.23) **	0.60 (0.23) *	
	GCoM member 2014 or after					0.09 (0.13)	0.09 (0.14)	
H2	Member in 1 network							0.09 (0.12)
	Member in 2 networks							0.33 (0.15) *
	Member in 3 networks							0.30 (0.31)
H3	GDP 2016 (in thousands)		0.01 (0.00) ***	0.01 (0.00) **	0.01 (0.00) **	0.01 (0.00) *	0.01 (0.00) *	0.01 (0.00) *
	Population (100 000)	0.00 (0.00)	0.00 (0.00)	−0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	−0.00 (0.00)	−0.00 (0.00)
	Level of adaptation legislation: executive	−0.19 (0.17)	−0.30 (0.16)	−0.33 (0.17)	−0.30 (0.16)	−0.43 (0.17) **	−0.45 (0.17) **	−0.37 (0.17) *
	Level of adaptation legislation: legislative	0.28 (0.16)	0.24 (0.16)	0.26 (0.16)	0.23 (0.16)	0.11 (0.17)	0.13 (0.17)	0.18 (0.16)
	Asia	−0.44 (0.17) *	−0.53 (0.17) **	−0.49 (0.18) **	−0.51 (0.18) **	−0.48 (0.18) **	−0.45 (0.19) *	−0.46 (0.18) *
	Europe	−0.30 (0.22)	−0.71 (0.24) **	−0.72 (0.24) **	−0.71 (0.24) **	−1.12 (0.30) ***	−1.12 (0.30) ***	−0.79 (0.25) **
	Latin America	−0.47 (0.23) *	−0.53 (0.23) *	−0.56 (0.23) *	−0.54 (0.23) *	−0.58 (0.23) *	−0.60 (0.23) **	−0.56 (0.24) *
	North America	−0.36 (0.25)	−0.98 (0.30) **	−0.99 (0.30) ***	−0.98 (0.30) **	−1.04 (0.30) ***	−1.06 (0.30) ***	−1.01 (0.31) **
	Oceania	−0.24 (0.30)	−0.73 (0.33) *	−0.77 (0.32) *	−0.72 (0.34) *	−0.76 (0.33) *	−0.79 (0.35) *	−0.82 (0.34) *
	Log(theta)	10.17 (62.98)	10.68 (44.10)	10.80 (39.43)	10.68 (44.32)	10.87 (38.33)	10.94 (35.26)	10.87 (38.38)

	Parameter estimates: zero-inflation model	Model 0	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
	Intercept	3.96 (0.74) ***	5.22 (0.90) ***	5.39 (0.93) ***	5.29 (0.92) ***	5.11 (0.90) ***	5.19 (0.97) ***	5.28 (0.93) ***
H1	C40 member before 2014			−1.87 (0.65) **			−1.75 (0.67) **	
	C40 member 2014 or after			−0.62 (0.45)			−0.71 (0.48)	
	ICLEI member before 2014				−0.80 (0.33) *		−0.79 (0.35) *	
	ICLEI member 2014 or after				0.44 (0.68)		0.36 (0.71)	
	GCOM member before 2014					−1.05 (1.14)	−0.59 (1.29)	
	GCoM member 2014 or after					−0.15 (0.37)	0.35 (0.41)	
H2	Member in 1 network							−0.68 (0.33) *
	Member in 2 networks							−2.51 (0.87) **
	Member in 3 networks							−18.28 (6456.69)
H3	GDP 2016 (in thousands)		−0.06 (0.02) ***	−0.06 (0.02) ***	−0.06 (0.02) ***	−0.06 (0.02) **	−0.06 (0.02) **	−0.06 (0.02) **
	Population (100 000)	−0.02 (0.00) ***	−0.02 (0.00) ***	−0.01 (0.01)	−0.02 (0.00) ***	−0.02 (0.00) ***	−0.01 (0.01)	−0.01 (0.00) *
	Laws 2	−2.31 (0.62) ***	−3.12 (0.70) ***	−3.21 (0.72) ***	−3.07 (0.70) ***	−2.99 (0.70) ***	−3.00 (0.73) ***	−3.11 (0.71) ***
	Laws 3	−0.05 (0.63)	−0.10 (0.70)	−0.23 (0.72)	0.08 (0.73)	0.16 (0.76)	0.24 (0.82)	0.34 (0.79)
	Asia	−0.58 (0.45)	−0.10 (0.48)	−0.35 (0.50)	−0.18 (0.48)	−0.17 (0.49)	−0.34 (0.52)	−0.30 (0.50)
	Europe	−4.70 (0.83) ***	−4.09 (0.88) ***	−4.32 (0.91) ***	−4.26 (0.89) ***	−3.93 (0.95) ***	−4.23 (0.99) ***	−4.15 (0.90) ***
	Latin America	−1.35 (0.66) *	−1.34 (0.71)	−1.33 (0.73)	−1.35 (0.73)	−1.34 (0.72)	−1.55 (0.77) *	−1.35 (0.75)
	North America	−3.47 (0.77) ***	−1.32 (0.92)	−1.27 (0.96)	−1.34 (0.92)	−1.31 (0.92)	−1.37 (0.95)	−1.25 (0.95)
	Oceania	−5.21 (1.32) ***	−3.69 (1.37) **	−3.50 (1.41) *	−3.70 (1.46) *	−3.70 (1.37) **	−3.67 (1.51) *	−3.47 (1.44) *
	AIC	999.68	978.64	973.37	979.28	977.67	975.77	970.94
	Log Likelihood	−480.84	−468.32	−461.68	−464.64	−463.83	−454.88	−458.47
	N	377	377	377	377	377	377	377

***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

significantly lower probability of having an API value zero compared to African cities (Model 0, zero-inflation model).

The existence of national legislation on climate adaptation is not significant in any model. This is not surprising, since only five out of 80 countries had legislation in place before 2014. The results concerning the association between the existence of a national non-binding strategic or guiding document (laws 2 in Table 4) are mixed. The existence of a guiding document is associated with an increased likelihood of having an API higher than zero, but negatively associated with API in the count model when GCoM membership is included as a covariate.

Next, we test H3 on the association between the wealth of the country that a city is located in and the city's API. The reason for testing H3 before H1 and H2 is that adding GDP into the models at this stage ensures that the wealth of the country is controlled for in all subsequent models that test H1 and H2. Since H1 and H2 are our primary hypotheses of interest, we wanted to present them first in the hypotheses section above.

The connection between GDP and higher API is statistically significant also when the city's location is controlled for (Model 1). GDP remained significant in all count and zero-inflation models (Models 2–6), indicating there is an association between GDP and higher API regardless of network participation, and the probability of having a value zero is lower in wealthier cities. All in all, these results support H3.

H1 was tested in zero-inflated Models 2 to 5 and count Models 2 to 5. The zero-inflated Models 2 and 3 show that membership of C40 and ICLEI decrease the probability of API being zero when a city has joined the network before 2014. Model 4 shows that membership of GCoM is not significant. The results are similar when all memberships are in the same model (Model 5).

Count Models 2 and 3 show that membership of ICLEI or C40 is not connected to higher API. However, cities which joined the GCoM network before 2014 have significantly higher API scores than others, controlling for geographic location and wealth (Model 4). These results are reproduced when all memberships are in the same model (Model 5). This is because almost all of these cities are members of the former Covenant of Mayors: out of 23 cities, 21 are in western Europe. The remaining two cities are in Canada and Mexico. In the dataset, 13 European cities are not members of GCoM, 12 of them in Russia. Their average API is clearly lower than among the European members of GCoM, which is probably why controlling by continent has not made the result insignificant. The effect of GCoM on API is not supported by standard negative binomial models (Supplement 2), so this result needs to be interpreted with caution.

H2 was tested in Model 6 by studying whether membership of multiple networks is associated with a higher API than membership of just one network. Being a member of two networks before 2014 was significantly connected to both higher API and a smaller probability of having an API value equal to zero (Model 6). Being a member of one network decreases the probability of a zero value (Model 6, zero-inflation part), but is not significant in increasing API (the count-part). Being a member of all three networks is not significant, but this is probably because only three cities were members of all three networks before 2014. These results are also supported by standard negative binomial models (Supplement 2). Network membership was not significant in any of the models, if the city had joined 2014 or later.

Adding GDP, memberships of C40 and GCoM, and the number of network memberships improves the model fit according to both measures used (AIC and Log Likelihood). Adding ICLEI memberhip improves only the Log Likelihood of the model. Analysis of Pearson residuals indicate a reasonably good fit to the data for all models (Supplement 4).

5. Discussion

This article began with the observation that there are high expectations that TMNs will propel cities into ambitious climate adaptation. Few studies, however, have looked into the validity of this claim, and the ones that have are limited to a few cases or specific geographic areas (Woodruff, 2018). We statistically tested whether network members are more advanced in climate change adaptation planning than other large cities, using a dataset that includes cities from all over the world and estimating a set of zero-inflated negative binomial regression models.

Our results support the claim that TMN members are more likely to have started climate change adaptation planning process than other cities. Members of C40 and ICLEI are less likely to have an API of zero than other cities when wealth, geographical location and legislation are controlled for. Members of the GCoM network have overall higher APIs than other cities. Being a member of two networks is associated with higher API scores and being a member of one of them increases the likelihood of a city's API being higher than zero.

We found that cities in wealthier countries are members of these networks more often than those in less wealthy countries. Even though wealth partly explains higher API scores through its effects on network membership, wealth also has a direct effect on API (i.e. wealthy cities have a higher API scores when network membership is controlled for).

Does all this mean that network membership supports cities in their climate change adaptation planning? With the kind of cross-national data used here, it is not possible to establish firmly the direction of causality. However, we did test the hypotheses separately for cities that joined before our data collection (2014) and after, and these tests lent further support to the interpretation that network membership does support the adaptation process. Those cities that had joined networks before 2014 had been more likely to have started the adaptation process than non-members, but this did not apply to those cities which joined later. Also, being a member of two networks before 2014 was connected to higher API, while being a member of two after that date was not.

If it were the case that cities already active in adaptation would be more likely to join the network, it would also be logical to find an association between higher APIs for cities that joined the networks after Araos et al. (2016b) measured their adaptation progress in 2014. We found no such association.

Kern and Bulkeley (2009) found that the most active core members of TMNs are often the founding members or those who join early, while the cities joining only after their neighbours or collaborators may adopt more passive roles. To establish whether this is the case, or whether networks actually push cities to action, would necessitate a full second round of data collection on adaptation initiatives in all cities included in our sample and analysis of their API scores both before and after joining the network. This should be done in future research.

In addition to the shortcomings imposed by our cross-sectional dataset, this study has other limitations. First, we concentrated on large cities. Results could be different for small or medium-sized cities. Second, several large urban areas with adaptation activities were not included in the dataset, since they did not offer information in the thirteen languages used in the data collection. Third, there is always the possibility of human error. Some cities may have had adaptation documents that were not found, leading to underestimated API. Fourth, country-level factors like GDP and location may not give a perfect picture about the capacities of the cities. However, they are the best proxies for which reliable data were available. Fifth, API is based on planning documents. Therefore, this study does not reveal if cities implement these plans or not. Global level analysis of implementation is another important topic for future research. Also, independent adaptation by citizens, the private sector and NGOs were beyond the scope of this study.

At the beginning, we noted that research on TMNs has often focused on certain, often high-capacity, cities and regions (Bansard et al., 2017) and may create an illusion about the cities on the front line of adaptation, while in reality only a handful of cities participate (van der Heijden, 2018). The cities in less wealthy countries may lack the necessary resources to join networks. Even among the ones that do participate, not all are active (Kern and Bulkeley, 2009), nor gain access to the benefits (Lee, 2015).

Our results show that many large cities remain outside the global networks, especially in less wealthy countries. Also, they show that cities located in poorer countries, especially outside the networks, have advanced less in the adaptation process. This is problematic, since urbanisation and population growth are rapid in less wealthy countries (UN-DESA, 2015), where climate change vulnerability is often high as well (Shi et al., 2016; van der Heijden, 2018). Considering the strong role cities from wealthy countries have in the networks, it is probable that simply joining the networks is not a solution.

Overall, our results show that much improvement is needed in adaptation planning in cities. This is true also for cities that belong to TMNs and cities in wealthy countries. Each of the networks we studied had many members with API scores of zero, and none of them had an average API close to 8, the highest figure on our scale.

In our results, network membership was significant even when GDP was controlled for. This lends some support to Lee (2015) argument that the attributes of the cities are more important drivers of their climate policy practices than the attributes of the host country. However, we did find that wealth, as a country attribute, does influence adaptation planning progress independent of the effect occurring through network membership. Wealth has also been found to be a driver of national level adaptation (Berrang-Ford et al., 2014). It has also been found that participation in networks supports cities especially when they lack state-level support (Bulkeley et al., 2003; Heidrich et al., 2016; Busch et al., 2018; Reckien et al., 2018). In our data, all cities from less wealthy countries with an API score of a perfect 8 participated at least in one network.[6]

It has been noted that the climate plans of C40 members from different contexts are remarkably similar, even though one could assume that different practices are needed (Heikkinen et al., 2018). While this similarity does not necessarily follow from network membership (Heikkinen et al., 2018), previous studies have also criticised networks for being too conservative and reinforcing the status quo (Acuto, 2013; Bouteligier, 2013; van der Heijden, 2017; Heikkinen et al., 2018). Also, a good solution may be less efficient or even harmful when exported to another context (Gupta et al., 2015; van der Heijden, 2017). It should be critically considered whether traditional large-scale master planning is the best way to tackle climate change-related risks in cities located in less wealthy countries (Shi et al., 2016).

Therefore, networks should consider developing new ways to act that would support context-based actions and more fundamental changes. C40 has taken steps in this direction by introducing personalised climate advisors. However, this is a costly method and therefore not offered to all members (C40, 2017 personal communication[7]). This again raises the question of accessibility to the benefits (Lee, 2015), which may lead to a situation in which the cities most needing support do not get it. Also, to have greater impact, networks might want to consider how non-members could benefit from their work.

6. Conclusion

Our analysis shows that the networks do have potential to support urban adaptation, but there is also room for improvement. Even among network members, the average and median APIs are not close to the maximum. Since API only measures the planning process, there is a risk that performance is even worse when it comes to actual action (see also Revi et al., 2014; Woodruff and Stults, 2016). The main implication of these results is that TMNs should consider how to further encourage adaptation among their member cities. Our comparison of countries with different levels of wealth and across geographic locations suggest that the networks should also consider giving special attention to cities in the less wealthy countries. Current and future mega-cities, facing a considerable need for adaptation, are located there (Bulkeley et al., 2011; Shi et al., 2016). It also seems that combining ambitious emission reductions and sustainable well-being in these countries is challenging (Sugiawan et al., 2019), which presents a further challenge to TMNs operating there. Based on this study, the level of adaptation process or networking in these countries is not high. Thus, the networks should be careful in planning how to support these regions so that cities are empowered to find the solutions that work best in their contexts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

[6] The two cities having API scores of 8 without participating in any of the networks analysed are: Marseille, France, and Sacramento, USA.

[7] See also: C40 City Advisors: https://www.c40.org/programmes/city_advisers.

CRediT authorship contribution statement

Milja Heikkinen: Conceptualization, Methodology, Investigation, Project administration, Writing - original draft. **Aasa Karimo:** Methodology, Formal analysis, Validation, Visualization, Writing - original draft. **Johannes Klein:** Conceptualization, Writing - original draft, Writing - review & editing. **Sirkku Juhola:** Conceptualization, Writing - review & editing, Supervision. **Tuomas Ylä-Anttila:** Conceptualization, Methodology, Writing - review & editing, Supervision.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.120474.

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