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Economic growth and income inequality increase the carbon intensity of human well-being for Canada's provinces

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Reducing the carbon intensity of human well-being (CIWB) is a potential form of climate action. We conduct a preliminary analysis of the effects of economic growth and income inequality on the CIWB of Canada's provinces, and find that both increase CIWB in this sub-national context. We also find that their effects are symmetrical, meaning that positive and negative changes in economic growth and income inequality result in the same proportional changes in CIWB. Therefore, and while incredibly difficult to do, it is possible that efforts to reduce income inequality and economic growth are potential pathways to reducing CIWB.

A vibrant area of interdisciplinary research focuses on the structural characteristics of societies that shape their CIWB[1–11]. The CIWB is typically operationalized as an adjusted ratio of per capita carbon emissions and average life expectancy, or in broader terms, the amount of carbon emitted per unit of well-being. Research on CIWB and related topics has grown rapidly in the past 10–15 years[12–18], yet its roots largely trace back a half century to an analysis published by Mazur and Rosa[19], which illustrated that societies can achieve relatively high levels of human well-being without consuming enormous amounts of fossil fuels and other natural resources.

We consider reducing CIWB to be a potential form of climate action, as doing so can involve reducing carbon emissions while further enhancing human well-being, or at minimum, reducing emissions while maintaining existing levels of well-being. A fundamental empirical question, then, is how do the structural characteristics of societies shape their CIWB? And in the spirit of the special collection of *npj Climate Action* in which this appears, which structural characteristics serve as barriers or pathways to this potential form of climate action? While scholars have focused on a range of political-economic and demographic characteristics as anthropogenic drivers of CIWB, economic growth and income inequality are among the most commonly studied, with both cross-national and sub-national analyses assessing the extent to which they effect CIWB[1–3,6,14].

Here, we modestly advance this research with a focus on the effects of economic growth and income inequality on CIWB for Canada's ten provinces for the 2000–2017 period. Consistent with much prior research on CIWB and similar topics, we measure economic growth as GDP per capita, and income share of the top 10% serves as our measure of income inequality. In addition to estimating the effects of economic growth and income inequality, we also assess if their effects on CIWB are asymmetrical, meaning that positive and negative changes in an independent variable differentially affect the dependent variable.

This is the first study to analyze these relationships, even preliminarily, in a longitudinal, Canadian cross-province context. Canada is among the world's nations with the largest carbon emissions, ranking tenth for total emissions and ninth for per capita emissions in the year 2020[20]. Regarding human well-being, Canada was ranked twenty-third among all nations in average life expectancy at birth in 2020[20]. These national-level data, while useful and important, overlook variation between provinces.

Figure 1 provides a map of Canada's ten provinces and plots out CIWB, GDP per capita, and the income share of the top 10% for each province for the 2000–2017 period. As the plots show, there is notable variation in CIWB between provinces, as well as notable changes through time across provinces (e.g., Alberta exhibits the highest and Quebec the lowest CIWB levels). The same applies to GDP per capita and income share of top 10% (e.g., Alberta exhibits the highest levels of both, Prince Edward Island and Nova Scotia exhibit the lowest and very similar levels of GDP per capita, Prince Edward Island exhibits the lowest levels of income share of top 10%). For the overall dataset, both GDP per capita and income share of the top 10% are positively correlated with CIWB (CIWB correlation with GDP per capita = 0.610, CIWB correlation with income share of top 10% = 0.283).

Figure 2 provides coefficient plots the estimated effects of GDP per capita and income share of the top 10% on CIWB for the provinces, derived from a series of two-way fixed effects models (both province-specific and year-specific fixed effects). Given the relatively small number of cases and modest number of annual observations, for

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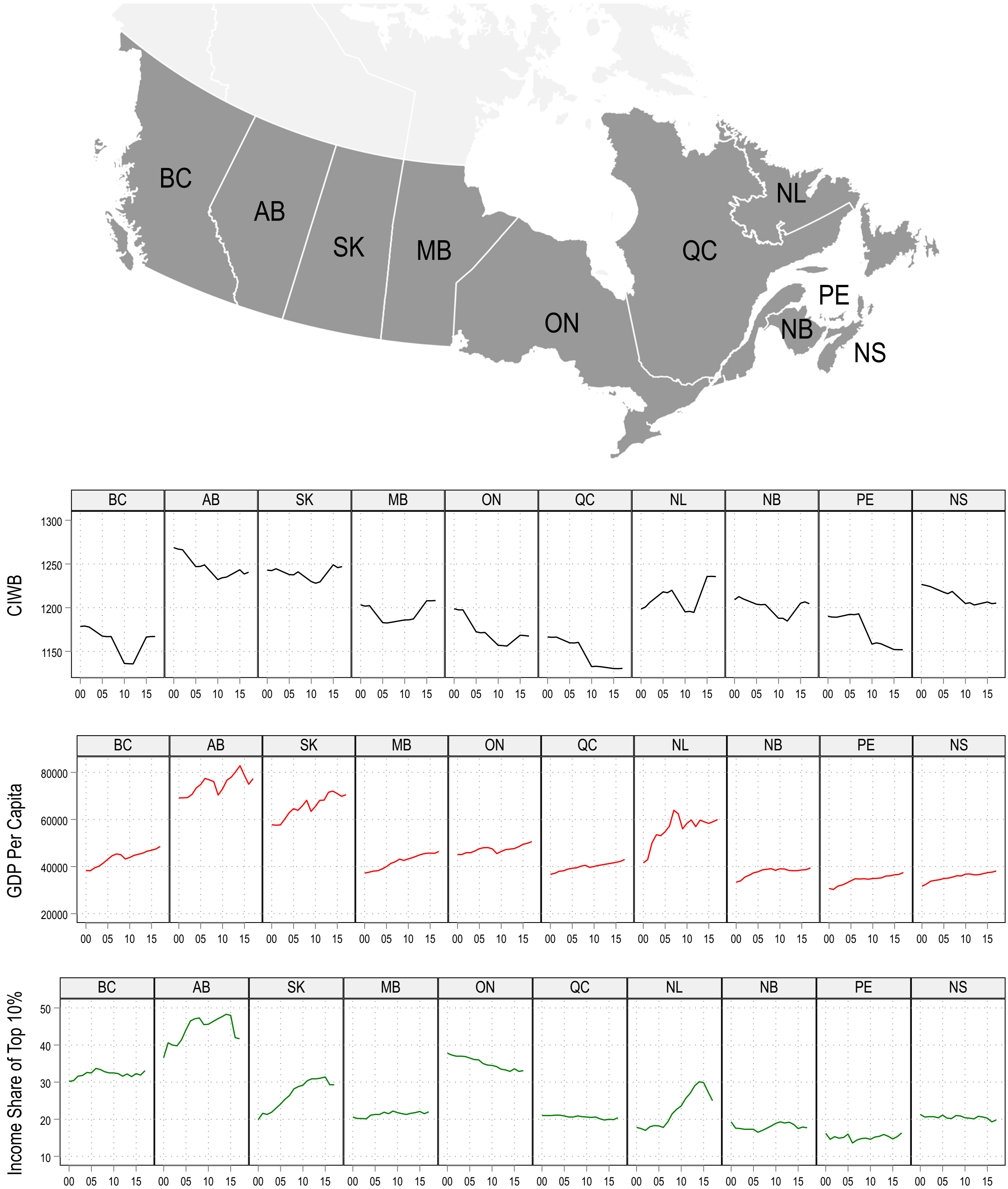

Fig. 1 | Map of Canada's provinces and province-specific plots of CIWB, GDP per capita, and income share of top 10%. Abbreviations are used for provinces: BC British Columbia, AB Alberta, SK Saskatchewan, MB Manitoba, ON Ontario, QC Quebec, NL Newfoundland and Labrador, NB New Brunswick, PE Prince Edward Island, and NS Nova Scotia; for CIWB, GDP Per Capita, and Income Share of Top 10%, provinces are listed in order from west to east based on their geographical locations.

robustness checks we use multiple standard error estimators: Cluster-Robust, HC2 Cluster-Robust, and Wild-Cluster Bootstrap. Elasticity coefficients and their 95% confidence intervals are reported, where the coefficient for the independent variable is the estimated net percentage change in the dependent variable associated with a 1 percent increase in the independent variable. Across all three models, the estimated effects of GDP per capita and income share of the top 10% are positive and statistically significant. The elasticity coefficient for GDP per capita is .086, meaning that a 1% increase in GDP per capita leads to a .086% increase in a province's CIWB. The elasticity coefficient for income share of top 10% is .032, meaning that a 1% increase in income share of the top 10% leads to a .032% increase in province-level CIWB.

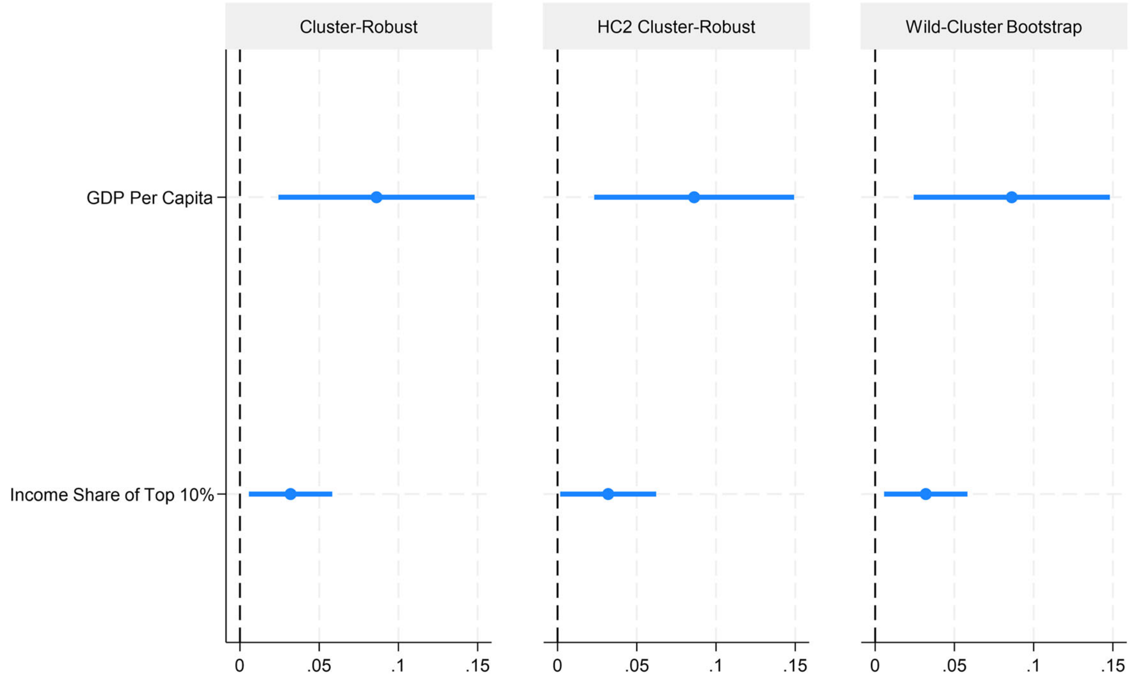

Fig. 2 | Coefficient plots for the estimated effects of GDP per capita and income share of top 10% on CIWB for Canada's provinces, 2000–2017. Elasticity coefficients and 95% confidence intervals reported; models estimated with *xtreg fe* in Stata 18; models include province-specific fixed effects derived from the within estimator and unreported year-specific fixed effects as intercepts; $N = 120$, with 12 observations per province.

Are the effects of economic growth and income inequality on CIWB asymmetrical? The analysis reported in Table 1 helps answer this question. We follow the standard approach to modeling asymmetry by including the positive and negative partial sums of the relevant independent variable in the estimated model. The Wald test for each model is not statistically significant, indicating that there is no asymmetry in the effects of GDP per capita or income share of top 10%. In other words, an increase and a decrease in GDP per capita or income share of the top 10% result in the same proportional change in CIWB. Therefore, the initial estimated effects reported in Fig. 2 are symmetrical and can be interpreted as the effect of an increase or decrease in GDP per capita or income share of the top 10% on province-level CIWB.

In summary, we find that both economic growth and income inequality have positive effects on CIWB for Canada's provinces. These results are generally consistent with past cross-national research and sub-national research focusing on the United States[1–3,6,14]. Given that reducing CIWB is a potential form of climate action, our analysis suggests that these two political-economic characteristics, in general, are barriers to such action. However, since their effects are symmetrical, it is possible that efforts to reduce income inequality and economic growth are potential pathways to reducing CIWB in this sub-national context. We acknowledge the enormous difficulties that this may pose, especially given the "growth at all costs" perspectives that largely dominate society. A fruitful initial strategy, then, might be to focus on reducing income inequality while pushing for more equitable forms of growth and advancing notions of sufficiency[21,22]. Finally, this analysis is very preliminary. Much more research is needed to understand the structural barriers and pathways to reducing province-level CIWB in Canada, and elsewhere, including the underlying mechanisms that shape the relationships between CIWB, economic growth, and income inequality.

Methods and data

The analyzed dataset consists of the ten provinces in Canada (Alberta, British Columbia, Manitoba, New Brunswick, Newfoundland and Labrador, Nova Scotia, Ontario, Prince Edward Island, Quebec, Saskatchewan). Yearly observations for each province from 2000–2017 are included with the exception of 2003, 2004, 2008, 2009, 2013, and 2014. These are the years in which data are currently available for both the dependent variable and the key independent variables, and the excluded years in the 2000–2017 range are due to the limited availability of average life expectancy data for the provinces. Overall, the analyzed dataset consists of 12 observations for each province, yielding a total of 120 observations.

The dependent variable, CIWB, is a ratio of production-based per capita CO_2 emissions (in metric tons) as the numerator and average life expectancy at birth as the denominator. The emissions data are obtained from Canada's Official Greenhouse Gas Inventory (https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/inventory.html). The life expectancy data are gathered from Statistics Canada (https://www.statcan.gc.ca/en/start).

Using a well-established approach to ensure that neither the numerator nor denominator disproportionately drives the CIWB ratio[1,4,8,10,12], a correction factor is added to CO_2 emissions per capita to make the coefficients of variation equal. We then scale the ratio, multiplying it by 100. In particular, CIWB is calculated as $[(CO_2PC + 801.9638671875)/LE] * 100$, where CO_2PC is CO_2 emissions per capita in metric tons and LE is average life expectancy at birth in years. We use the community contributed *eiwb* command in Stata (version 18) to calculate the province-level CIWB measures[23].

The two independent variables, GDP per capita (chained 2012 dollars) and income share of top 10% (based upon after tax income for all tax filers), are both obtained from Statistics Canada (https://www.statcan.gc.ca/en/start).

All models are estimated using the *xtreg fe* command in Stata (version 18), and include both province-specific and year-specific fixed effects. All nonbinary variables are transformed into logarithmic form. This means the models estimate elasticity coefficients where the coefficient for the independent variable is the estimated net percentage change in the dependent variable associated with a 1 percent increase in the independent variable.

The general equation for the estimated models reported in Fig. 2 is as follows:

$$CIWB_{i,t} = \beta_1 GDP\ per\ capita_{i,t} + \beta_2 Income\ Share\ of\ Top10\%capita_{i,t} + \alpha_i + u_t + \varepsilon_{i,t} \tag{1}$$

Table 1 | Asymmetric regression of CIWB for Canada provinces, 2000–2017

	CR	CR	HC2CR	HC2CR	WCB	WCB
GDP Per Capita (+)	0.101**		0.101^		0.101^	
	(0.028)		(0.032)		[3.61]	
GDP Per Capita (-)	0.036		0.036		0.036	
	(0.073)		(0.078)		[0.049]	
Income Share of Top 10% (+)		0.035^		0.035		0.035
		(0.017)		(0.020)		[2.07]
Income Share of Top 10% (-)		0.019		0.019		0.019
		(0.034)		(0.047)		[0.55]
Asymmetry (Wald Test)	1.17	0.13	1.08	0.07	1.17	0.13

Elasticity coefficients and 95% confidence intervals reported; models estimated with *xtreg fe* in Stata 18; models include province-specific fixed effects derived from the within estimator and unreported year-specific fixed effects as intercepts; $N = 120$, with 12 observations per province; Wald Tests are not statistically significant.
CR clustered-robust, HC2CR HC2 clustered-robust, WCB wild-cluster bootstrap.
$^{**}p < 0.01$ $^{*}p < 0.05$ $^{\wedge}p < 0.10$ (two-tailed); standard errors in parentheses; t statistics for WCB models in brackets; GDP Per Capita asymmetry models control for Income Share of Top 10%; Income Share of Top 10% asymmetry models control for GDP Per Capita.

Due to the relatively small number of cases and modest number of annual observations, for robustness checks, each reported model involves a different standard error estimator: Cluster-Robust, HC2 Cluster-Robust, or Wild-Cluster Bootstrap. Cluster-Robust is the most common in traditional fixed effects panel models. The HC2 Cluster-Robust and Wild-Cluster Bootstrap standard errors are considered more suitable for datasets with smaller numbers of panels and therefore fewer clusters, and tend to produce slightly larger confidence intervals than Cluster-Robust standard errors and other approaches, usually leading to more conservative hypothesis testing[24]. For the HC2 Cluster-Robust model the p-values are computed using adjusted degrees of freedom[25], and for the Wild-Cluster Bootstrap standard errors we specify normal error weights, symmetric p-values, and for reproducibility, we include a seed[26]. Given the overall small sample size, we flag statistical significance for two-tailed tests at the 0.01, 0.05, and 0.10 levels.

For the analysis reported in Table 1, we follow the standard approach to modeling asymmetry by including the positive and negative partial sums of each income inequality measure in the models[10,27]. $x_{i,t}$ is decomposed as $x_{i,t} = x_{i,0} + x^{+}_{i,t} + x^{-}_{i,t}$, where $x^{+}_{i,t}$ and $x^{-}_{i,t}$ are partial sums around a threshold of zero:

$$x^{+}_{i,t} = \sum_{j=1}^{t} \Delta x^{+}_{i,t} = \sum_{j=1}^{t} \max(\Delta x^{+}_{i,t}, 0) \tag{2}$$

$$x^{-}_{i,t} = \sum_{j=1}^{t} \Delta x^{-}_{i,t} = \sum_{j=1}^{t} \min(\Delta x^{-}_{i,t}, 0) \tag{3}$$

In other words, two series are generated that estimate the running totals of the positive ($x^{+}_{i,t}$) and negative ($x^{-}_{i,t}$) changes in $x_{i,t}$. A Wald test is then used to test whether the coefficients of the two sums are equal. If they are statistically different then there is evidence of asymmetry. The partial sums are generated in Stata 18 using the community contributed *xtasysum* command[28].

The analyzed dataset and all Stata code used for the reported analysis are available from the lead author upon request, and will also be posted on the lead author's lab website.

Data availability

The data that support the findings of this study are available upon reasonable request from the lead author and will be publicly available on their lab's website.

Code availability

All Stata commands used in the analysis are available upon reasonable request from the lead author and will be publicly available on their lab's website.

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Author contributions
A.J. designed the study, conducted the analysis, created Fig. 2 and Table 1, and took the lead in drafting the manuscript. T.G. took the lead in data collection, created Fig. 1, provided feedback on the analysis, and helped draft the manuscript. R.T. provided feedback on the analysis and helped draft the manuscript. Y.K.M. provided feedback on the analysis and helped draft the manuscript. M.S. provided feedback on the analysis and helped draft the manuscript. N.V. provided feedback on the analysis and helped draft the manuscript. G.G. provided feedback on the analysis and helped draft the manuscript.

Competing interests
The authors declare no competing interests.

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