CANADIAN JOURNAL of UNDERGRADUATE RESEARCH

# Space Race

*"The Space Race began in the wake of World War II, when scientific development was at an all-time high. Motivated by military, economic, and exploration-based interests, the Americans, Russians, and Chinese competed for prominence in space exploration, resulting in significant technological and scientific advances throughout the 1950s and 1960s." (p.7)*

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## Greenhouse Gas Emissions

*"At this point, environmental degradation will begin to decrease as income continues to rise, resulting in an inverted U-shaped curve. Therefore, if appropriate policies are taken, economic growth can eventually lead to environmental improvement" (p.22)*

## Childhood Victimization

*"…one in three Canadians have experienced at least one form of childhood victimization before the age of 15…Childhood victimization can have adverse lifelong and even intergenerational impacts." (p.16)*

# CANADIAN JOURNAL *of* UNDERGRADUATE RESEARCH

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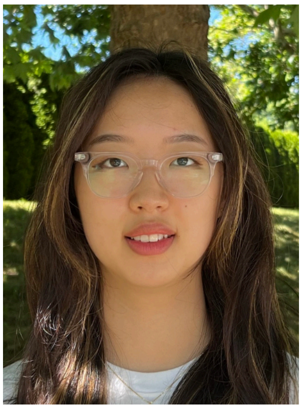
This issue is published on the traditional, ancestral, and unceded territory of the Coast Salish Nations, including xʷməθkʷəy̓əm (Musqueam), Sḵwx̱wú7mesh (Squamish), and səlilwətaɬ (Tsleil-Waututh).

# Letter from the editors-in-chief



We are very honoured to present Volume 8 Issue 1 of the Canadian Journal of Undergraduate Research (CJUR), showcasing four exemplary articles written by hardworking undergraduate students at post-secondary institutions across Canada. Spanning the realms of space exploration, public health, engineering physics, and environmental sciences, Volume 8(1) allows insight into different phenomena that surround us. We at CJUR are proud to recognize and celebrate undergraduate researchers' tremendous accomplishments by maintaining a platform through which their work can be disseminated.

Currently, CJUR has 32 active papers in the editorial and copyediting queue, all of which are of utmost quality. We are truly impressed by the research and reviews put forward by our undergraduate authors. We look forward to receiving even more manuscripts from various disciplines throughout the year, as CJUR would not be possible without the input from our authors. We would also like to recognize our graduate, postdoctoral, and faculty reviewers, who have all put in tremendous amounts of work to make our dream into reality.

As new editors-in-chief, we are incredibly excited to navigate our way through this academic year with our new editorial board. This year, we had seven new editors join our team. They have been working tirelessly to smoothen the transition process and to ensure that all manuscripts are receiving the highest calibre of care. It is our great privilege to be able to work with such an enthusiastic group of editors. In addition, none of this would have been possible without our senior advisor, whom we would like to thank for the mentorship and insightful expertise.

We hope that you will enjoy Volume 8 Issue 1 as much as we did, and we thank you for your endless support.

Yours sincerely,

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EDITORS-IN-CHIEF 2023-2024

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# The Space Race between the 1960s and 1970s

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Abstract "The Space Race Between the 1960s and 1970s and its Lasting Impact on Space Exploration" is an analysis of the progression of science throughout the aforenamed decades and the impact that space exploration had on these achievements. With a focus on the telemetry system of the Voyager Missions, this paper explores topics such as colour photography, satellites, and radio waves. It will explain concepts such as Golay coding, which allows higher resolution photographs to be transmitted from space and radio waves, thus allowing scientists to measure characteristics of other planets in our solar system (i.e., atmospheric composition). This paper will discuss how public support, and consequently funding, for space exploration has declined over time and how this trend has affected the progress of organizations such as NASA. The international space race was an instrumental part of scientific development in human history, and this paper aims to bring light to both its successes and failures.

## INTRODUCTION: THE SPACE RACE AND THE COLD WAR

The Space Race began in the wake of World War II, when scientific development was at an all-time high. Motivated by military, economic, and exploration-based interests, the Americans, Russians, and Chinese competed for prominence in space exploration, resulting in significant technological and scientific advances throughout the 1950s and 1960s. However, as goals were met and priorities shifted, funding and public support for space exploration began to decline among the American population. For example, the 1977 launch of the Voyager Missions—two of the most groundbreaking space exploration missions in history—were affected more directly by this cultural shift than any project before them. This paper will explore pivotal moments of the Space Race during the 1970s. It will describe the development of colour imaging in spacecrafts and the necessary coding techniques required for its transmission, radio science used for communication with the spacecrafts, and extraterrestrial communication efforts. In addition, this paper will examine the reasons for both the success of space exploration in this period as well as the failure of the Race to maintain its initial enthusiasm and optimism. Through a detailed discussion of how international competition for dominance fueled technological and scientific throughout the aforementioned decades, the devastating decline of funding and interest in space exploration will be explained.

### Space Exploration in the Kennedy Era

In his first speech as an honorary visiting professor at Rice University in the autumn of 1962, US President John F. Kennedy said that "[t]he exploration of space… is one of the great adventures of all time, and no nation which expects to be the leader of other nations can expect to stay behind" (National Archives, 1962). In the post-World War II environment, leadership of nations was also presumed to require nuclear dominance. Rockets would play a key role in both the Space Race and the Cold War, and the United States had made great efforts to ensure that the best wartime scientists, having emerged during the scientific advancements of WWII, were on the side of the Americans as opposed to the Soviets or the United Kingdom. This was done through Operation Paperclip, a program organized by the American Office of Strategic Services (OSS) and the Joint Intelligence Objectives Agency (JIOA) to recruit Nazi German scientists in the years between WWII and the Cold War (Huzel, 1995, p. 1). Americans chose this particular group of scientists not only for their expertise in explosives and other military-based advancements, but also to remove them

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(and their knowledge) from Germany and prevent them from providing further insight to the USSR and/or UK (Huzel, 1995, p. 1). Many of the leading scientists recruited through this program were rocket scientists including Wernher von Braun and Arthur Rudolph (Huzel, 1995, p. 1). Further, the American government formed the National Advisory Committee for Aeronautics (NACA) in an attempt to streamline government advancements (River).

Despite American post-war efforts, however, Soviet plans for space satellites were already in place in the 1950s. The Space Age was initiated by the Soviet Union with the creation and launch of the first of the Sputnik spacecraft in 1957 and claimed the title of the first space satellite (Klein, 2003, p. 6). The National Aeronautics and Space Administration (NASA) was established by the United States in the following year (Dick, 2008; Newell, 2011, "No page number" section). NASA was created as a specialized branch of NACA and as a means to compete with the Soviets (River). Between 1962 and 1967, NASA planned to "double the number of scientists and engineers" dedicated to space exploration and "increase its outlays for salaries and expenses to $60 million a year;" to "invest some $200 million in plant and laboratory facilities;" and to "direct or contract for new space efforts over $1 billion," an amount equivalent to almost $9 billion today (National Archives, 1962). Setting foot on the moon became "a high national priority" for the Kennedy government (National Archives, 1962). Unfortunately, the opinion of the public did not quite match this political enthusiasm. By the time that goal was accomplished in 1969, the American public had become increasingly less interested in funding NASA, especially as the Vietnam war increasingly occupied their minds and wallets (Bell, 2015). As the NASA Historical Data Book shows, "NASA's annual budget, which had reached $5 billion in the mid-1960s and stood at almost $4 billion in 1969, was reduced to $3.7 billion in 1970 and just over $3 billion in 1974" (NASA Historical Data Book). The progression from the Kennedy-era to Nixon's presidency played a large role in these budget cuts. During his years in office, Nixon declined funding for Apollo 18, 19, and 20 and declined the first proposal for the Grand Tour missions. However, after the price tag dropped more than two thirds of its original amount, Nixon approved a later proposal for the missions (Bell, 2015, p. 62-63). With cheaper missions being proposed, the Space Race was able to continue into the 1970s despite its diminishing of support.

## The Voyager Missions

In the 1960s and 70s, NASA designed and launched multiple spacecraft. Mariner 2 (1962) was the "first successful interplanetary mission of the human species," Viking 1 and 2 were a pair of landers which touched down on the planet Mars in 1976, and the Voyager 1 and Voyager 2 missions in 1977 were robotic probes that reached interstellar space in 2012 and 2019 respectively (The Planetary Society, 2019). Their missions continue to the present day (Bell, 2015, p. 16; The Planetary Society, 2019)

The Voyager spacecrafts were launched on what became known as the Grand Tour, a "once-every-176-year planetary alignment" allowing a single spacecraft to travel past all of Jupiter, Neptune, Uranus, and Saturn in a sort of slingshot motion (Bell, 2015, p. 14). Equipped with the best technology that the 1970s could offer, Voyager featured

> wide-angle and resolution cameras for imaging and spacecraft navigation; radio systems for studying gravitational fields and planetary radio emissions; infrared and ultraviolet spectrometers to measure chemical compositions; a polarization sensor for surface, atmosphere, and planetary ring composition; a magnetometer measuring magnetic fields; four devices for studying charged particles, cosmic rays, plasma, and plasma waves (Bell, 2015, p. 23).

Despite the decline of public support in the late 70s, the most advanced technology available was being applied to space exploration, just as President Kennedy had promised. After Voyager 1 and 2 "swept by the Jupiter, Saturn, Uranus, and Neptune systems," influential planetary scientist Carl Sagan suggested that "[i]t is our great privilege to be alive at that first moment when ignorance is converted into knowledge" (pangea, 2010; The Planetary Society, 2019)

NASA's strong connection to the US military, primarily via space science, gave them access to technology and funding at a time when direct support was lagging (Newell, 2011, "No page number" section). In fact, "[m]ost of the space scientists who came to NASA in the fall of 1958 had been associated with the Army, Navy, or Air Force rocket or satellite research programs" (Newell, 2011, "No page number" section). Due to mutual benefit and interest, through the 1940s and 1950s, rocket research was supported by the military and NASA as well as the aerospace companies who were also recorded as participating in the satellite program of the International Geophysical Year (IGY) (Newell, 2011, "No page number" section). Collaboration between NASA and the military was organized as a "10-man group with 5 members from each organization" that met monthly from 11 August 1959 onward; they called themselves the Unmanned Spacecraft Panel of the Aeronautics and Astronautics Coordinating Board (Newell, 2011, "No page number" section).

In 1979 and 1980, researchers at NASA recovered the first colour pictures of Jupiter and Saturn from Voyager imaging systems (Cherewitzo, n.d.a). NASA believed these cameras would be able to "observe and characterize the circulation of the planetary atmosphere, provide limits on atmospheric composition, determine the wind velocities… search for new rings… [and] [p]rovide support images to assist other onboard investigations" (Imaging Science Subsystem). These imaging systems were a modification of those used on the earlier Mariner missions, which were not in colour. Acquiring these colour transmissions required sending three times the amount of data from three copies of the vector space in which we find our data, and thus, required more advanced methods of error coding to be able to successfully receive the images on Earth (Cherewitzo, n.d.a; Curtis, 2016, p. 54). The purpose of error coding is to remove as much error as possible from images being transmitted and received from space; as error coding became more advanced, error-correcting capabilities allowed for clearer reception imaging from the spacecrafts (Cherewitzo, n.d.b). Coding theory had originally been introduced when digital computing still relied on unreliable mechanical relays. If a single relay failed, the entire calculation would fail. It was thus necessary to be able to detect when and where errors had occurred, so the data could be retransmitted (Cherewitzo, n.d.b). The introduction of colour images from the Voyager systems required a version of error-detecting coding called the Golay (24,12) code, which uses only 3-error correcting but is capable of a much higher transmission rate (Cherewitzo, n.d.a). This means that Golay (24,12) is able "to correct three or less errors and to detect the presence of four errors" within an incoming transmission code from the Voyager spacecraft (Truong et al., 1989). More specifically, if there are less than three errors in the transmitted code, then the older and less advanced, Golay (23,12) is sufficient as a decoding technique; however, as soon as the number of errors detected in the transmission code is greater than or equal to three, the Golay (24,12) is required (Truong et al., 1989). Later, when Voyager 2 moved through its course onto Uranus and Neptune, the error code methodology changed again, switching to a Reed-Solomon code for higher error correcting capabilities and the use of VLA data gaps (Cherewitzo, n.d.a; Dolinar, 1988, p. 113). VLA data gaps are the "basis for a theoretical calculation of the performance" of the Reed-Solomon concatenated code; the "regularity of the gap cycle helps to eliminate the possibility of larger than average numbers of errors due to the gaps," allowing the decoder to correct the errors during the gaps (Dolinar, 1988, pp. 113-14). These developments in coding methodology are another example of the quickly developing scientific field in the 1970s and the application that it had to space exploration.

Since launching 38 years ago, the Voyager missions have maintained communications with Earth through their complex telemetry systems (Manz, n.d.). The primary method of communication between Voyagers 1 and 2 and Earth is via radio link (Langston, 2017). This connection runs between tracking stations on Earth and a dual-frequency radio system on the spacecraft (Langston, 2017). Since 1960, radio frequency channels have been expanded by eight orders of magnitude and the resolution used for tracking a spacecraft has been improved by a factor of 105 (Manz, n.d.). Because of advancements like these, four of the instruments on Voyager 1, as well as five on Voyager 2, are still being tracked, including the Cosmic Ray Subsystem, Low-Energy Charged Particles, Magnetometer, and Plasma Wave Subsystem (Mission Status, 2021). These developments have allowed the Voyager missions to achieve more complex goals than any NASA mission before them. Using high-resolution hyperspectral imagers, scientists at the Jet Propulsion Laboratory (JPL) at NASA could capture images from the Voyager spacecrafts at hundreds or even thousands of wavelengths simultaneously; this allowed JPL and NASA to view mineral content and other aspects of the spacecrafts' surroundings that would be impossible to see from a single visible-wavelength image (Manz, n.d.).

Radio science is now the last available form of communication with the Voyager spacecrafts, which featured

> harmonic, dual-frequency, high-power, spacecraft transmissions; use of new, highly-stable, temperature-controlled, radiation-hardened quartz; improved phase, group-delay, and amplitude stabilities in the spacecraft and ground radio systems; a novel attitude-control thruster configuration that minimizes accelerations along the Earth-spacecraft line-of-sight; planned trajectories that provide multiple planetary and satellite encounters with radio occultations by Jupiter, Saturn and its rings, Titan, Uranus, and possibly Callisto (Eshleman et al., 1977, p. 208).

The behaviour of radio waves has allowed scientists at NASA to study the atmosphere and ionosphere of Earth's neighbouring planets. As the spacecraft moves behind a planet and the radio wave connection attempts to pass through the planet, the characteristics of the radio frequencies that are returned to Earth are affected (Eshleman et al., 1977, p. 208). The angle of refraction that is returned to Earth as the radio signals pass through the planetary atmosphere is read as a function of time; this, combined with the information gained from the spacecraft trajectory, allows scientists to estimate the "refractivity of the atmosphere as a function of height" (Eshleman et al., 1977, p. 212). This, in turn, allows for the calculation of planetary temperatures and pressures (Eshleman et al., 1977, p. 209). Gravity fields of these planets give information about the average mass density of the surrounding moons as well as the internal structure of the planets Saturn and Uranus (Eshleman et al., 1977, p. 209).

## How the Voyager Missions Changed Our Outlook

In the seven years following the Voyager launches, humans have flown past every planet in our solar system, gaining a better understanding of the environment and qualities of each one. This allowed researchers to gain a much better understanding of the formation of our solar system and provided an opportunity to search for extraterrestrial life (The Planetary Society, 2019). An important antecedent for the latter was 1971's Project Cyclops (Project Cyclops, p. 1). The objective of this mission was "to assess what would be required in hardware, manpower, time and funding to mount a realistic effort, using present state-of-the-art techniques, aimed at detecting the existence of extraterrestrial intelligent life" (Project Cyclops, p. 1). The project was motivated by a lack of accurate estimates for how much intelligence was in the universe and, therefore, no way of knowing how far into space scientists should search (Project Cyclops, p.1). Since physics and chemistry are presumed to remain unchanged throughout our universe, "composition of the primordial material is commonly repeated elsewhere" as well as processes such as natural selection (Project Cyclops, p. 4). Planetary systems around the stars were thus thought to be the most probable location for life (Project Cyclops, p. 4).

In 1974, Search for Extraterrestrial Intelligence (SETI) transmitted the first-ever message dedicated to reaching extraterrestrials located 25,000 light-years away; this message was sent through the Arecibo radio telescope (Bell, 2015, p. 97). This decision, however, was quite controversial. The astronomer Sir Martin Ryle, a Nobel laureate, saw these efforts as irresponsible and a way of revealing the human location to possible interstellar enemies (Bell, 2015, p. 97). Stephen Hawking, Cambridge theoretical physicist and cosmologist, said that reaching out to alternate life forms might force us "to see how intelligent life might develop into something we wouldn't want to meet" (Bell, 2015, p. 98).

The Voyager missions also included a message for aliens— one that was unlike any before it. Called the 'Golden Record,' this message was created by Frank Drake, astrophysicist and radio electronics expert and Carl Sagan's Cornell University colleague. Drake is well known for the "Drake equation" which was "an attempt to mathematically estimate the number of intelligent civilizations in our galaxy by stringing together a bunch of probabilities" (Bell, 2015, p. 94). The Golden Record that he designed was a gold-plated 12-inch copper disk: it was a longplaying phonograph record (LP), as opposed to the engraved plaques used in all the other attempts to communicate with life beyond earth (Bell, 2015, pp. 91-94). The record included scientific and mathematical diagrams such as the composition of air as well as "an hour and a half of music (27 pieces in all), 116 digitized photographs, and a catalogue of terrestrial sounds (such as the chirping of crickets) and voices (such as short greetings in fifty-five languages, including a "hello from the children of Planet Earth" in English from Carl Sagan's then six-year-old son, Nick)" (Bell, 2015, pp. 101-103).

## CONCLUSION

The Space Race took shape in the 1960s. With the United States and NASA entering this race by extending their funding in an effort to chase Sputnik, more data was collected, research was improved, and scientists were able to advance technology tenfold, not only for space exploration but also for general use by the population. However, as the 1970s approached and public support declined, it became increasingly difficult to achieve the international goals set for space exploration. Further, as time goes on and space exploration becomes increasingly privatized (i.e., SpaceX), the declining government support for this scientific field is becoming more apparent. For example, in 2018, 45th President of the United States Donald Trump proposed to the US Congress that it might be a good idea to cut the budget of a number of missions – including Earth Science Missions and NASA Astrophysics' flagship missions - for the 2020s, as well as discontinuing NASA's Office of Administration (Siegal, 2019).

There is no doubt that massive scientific achievements can be credited to the concentration of brain power that came together after the second world war in the effort to get man into space after the second world war. From launching the first space satellite to collaborations with the military on the first colour pictures of Saturn and Jupiter, it is undeniable that many great accomplishments came out of this era. However, after at least a decade of major funding and attention was given to the international Space Race, the public began to realign its focus and NASA fell low on America's list of priorities. With inadequate funding for new missions and a controversial search for extraterrestrial life, space discovery was limited to the work of mathematicians and scientists who could only hope to have their work applied to live exploration in the future.

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## Conflicts of interest

The author declares no conflicts of interest.

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# Design of an asymmetrically biased triple Langmuir probe and accompanying diagnostics tool

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ABSTRACT A refined triple Langmuir probe design is described for use in a glow discharge device, which creates plasma by applying a large bias voltage across a neutral gas. The goal is to design a Langmuir probe which can measure the plasma temperature, density, and floating potential to within an order of magnitude while minimizing plasma perturbation. The probe functions in a plasma temperature range of 1-10 eV. First, an overview of the relevant theory is provided, followed by the design assumptions and a derivation of the working regime of the Langmuir probe. This working regime dictates the appropriate branch of Langmuir probe theory whose equations can be used to design the probe and extract the plasma electron temperature, density, and floating potential. Second, the probe's radius, length, and electrode spacing are derived using the applicable branch of Langmuir probe theory. The derived probe radius, length, and electrode spacing are 0.18 mm, 3 mm, and 55 mm, respectively. Third, an overview of the electrical design used to measure the triple probe voltages and currents is described. Finally, a discussion of the limitations and future work is provided, with methods listed to improve the specificity of the relevant theory and the accuracy of the probe measurements.

## INTRODUCTION

Recent developments in fusion-based energy have increased the demand for plasma physics research at an undergraduate level. As such, Queen's University is interested in providing a plasma physics undergraduate lab to teach plasma physics in a hands-on environment. This will be done using the Queen's glow discharge device, a type of plasma generator that creates plasma by applying a bias voltage across a neutral gas (H Conrads & M Schmidt, 2000). This article describes the development of an asymmetrically biased triple Langmuir probe (Kozhevnikov et al., 2021). The probe is asymmetrically biased as each of the three probes are biased independently of one another. Langmuir probes are conducting structures inserted into a plasma and biased over a voltage range. The current draw of the probe is plotted as a function of input voltage, and properties of the plasma can be extracted from the resulting I-V curve (Figure 1). These properties include the plasma electron temperature, floating potential, and density (Chen, 2016).

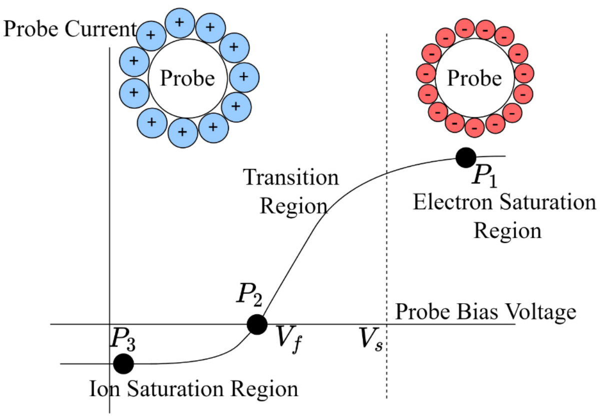


**Figure 1** I-V curve showing the placement of the three data points. These three data points will be curve fit to recover the original I-V curve and the recovered I-V curve will be analyzed to extract the plasma temperature, density, and voltage

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Langmuir probes are not universal devices and should be designed with an understanding of the type of plasma they will be measuring (Chen, 2003). As such, this work aims to design a triple Langmuir probe suitable for use in the Queen's University glow discharge device. The advantage of a triple Langmuir probe is its measurement speed (Kozhevnikov et al., 2021). Traditional Langmuir probes must sweep across the voltage range to generate an I-V curve and extract the plasma parameters, whereas triple Langmuir probes measure three points on the I-V curve simultaneously, making them an essential measurement tool for high-speed fusion reactions (Biswas et al., 2015). While glow discharge devices operate in steady state and do not require instantaneous measurement, a triple probe will provide a useful learning tool for students to compare the measurement techniques for both steady state and transient plasmas, and will provide a tangible example of the compromises required to measure high-speed plasmas.

## METHODS

### Determination of the working regime

The first step in designing a Langmuir probe is to determine the working regime of the plasma, which dictates which branch of Langmuir probe theory is applicable (Hippler et al., 2008). The probe presented here is designed to work in the Queen's University glow discharge device. Steady state glow discharge devices are a type of plasma generator that apply a direct current voltage across a neutral gas to create a plasma (DeWit, 2021). Furthermore, a diagram of the triple probe design is presented in Figure 2.

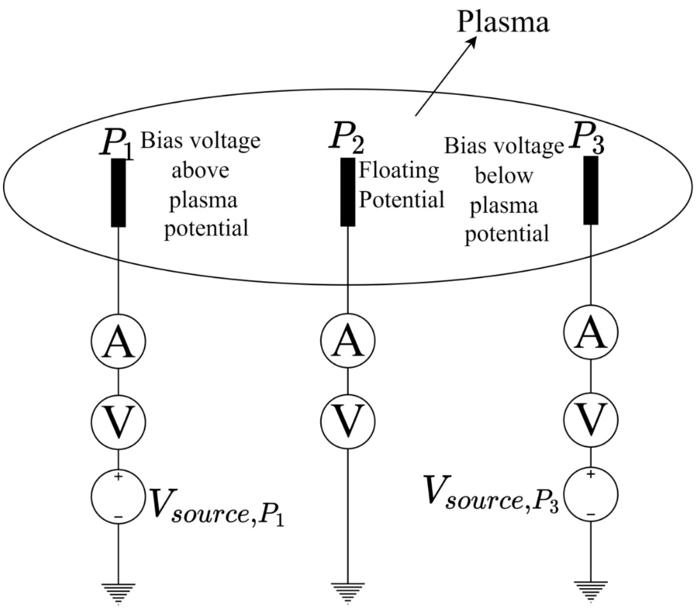


Figure 2 The triple probe design. The probe consists of three independent single probes for greater control over the acquisition of data.

When a biased Langmuir probe is inserted into plasma, a sheath of ions or electrons having a charge opposite to the probe bias forms around the probe, effectively shielding it from the bulk of the plasma. The length scale over which this shielding effect operates is known as the Debye length (Chen, 2016). The applicable branch of Langmuir theory depends on the geometric relationship between the probe radius $r_p$ and the Debye length $\lambda_D$. The sheath is assumed to be negligible if,

$$\lambda_D \ll r_p \quad (1)$$

(Chen, 2009, 2016; Lindner et al., 2023; Tichý et al., 1994). Edward DeWit, who worked previously on the Queen's glow discharge device, measured the Debye length $\lambda_D$ (5.7 ± 0.7) x $10^{-1}$ mm (DeWit, 2021). Thus, the sheath is negligible if,

$$r_{p,\min} \gg 5.7 \pm 0.7 \times 10^{-1} \text{ mm}, \quad (2)$$

DeWit used a probe with a radius $r_{p,DeWit}$ = 0.16 mm; however, they recommended reducing the probe radius because the larger probe surface area increased the voltage threshold required to enter the electron saturation region. This leads to the condition that the desired probe radius, $r_{p,desired}$, is constrained as follows:

$$r_{p,\text{desired}} < r_{p,DeWit} < r_{p,\min}. \quad (3)$$

Equation (1) cannot be satisfied under DeWit's recommendation, and thus sheath thickness must be considered in the design. Orbital Motion Limited (OML) theory applies to the thick sheath regime in a collision-less plasma and will be used to extract the plasma parameters (Tang & Luca Delzanno, 2014).

### Design assumptions

The range of plasma potentials $V_s$ experienced by the probe is constrained as:

$$0\text{ V} < V_s < 500\text{ V}, \quad (4)$$

which constrains the maximum voltage at the anode of the glow discharge device. The range of voltage differences between the probe bias voltage $V_b$ and plasma potential $V_s$ is constrained as:

$$10\ V \le |V_s - V_b| \le 100\text{ V}. \quad (5)$$

The upper bound of Equation (5) was set to ensure no electrical arcing and the lower bound was set to ensure reasonable resolution for the collected data. The electron temperature is constrained to be:

$$1\ eV \le T \le 10eV. \quad (6)$$

It is also assumed that the plasma is collision-less, such that plasma is not colliding within the sheath (Sheridan & Goree, 1991).

### Electrode geometry

Electrode geometry refers to a cylindrical electrode of length d and radius $r_p$. Equation (7) defines the ion and electron saturation currents of the probe:

$$I_{sat} = \frac{2er_p d}{n}\left(\frac{2e|V_s - V_b|}{m}\right)^{\frac{1}{2}}, \quad (7)$$

where $I_{sat}$ is the ion or electron saturation current, e is the fundamental charge, n is the plasma density, and m is the ion or electron mass, all other variables have been previously defined (Chen, 2016). The triple probe will consist of probes $P_1$,$P_2$, and $P_3$, which will be positively biased, unbiased, and negatively biased with respect to the plasma potential, respectively. Probes $P_1$ and

$P_3$ must draw currents above the electron and ion saturation currents, respectively. Drawing a current above the saturation current ensures a fully formed sheath and results in three distinct points for curve fitting (Figure 1).

## Electrode spacing

Probe electrodes are separated such that their measurements are independent and no electrical arcing occurs between probes. The probes interact with one another if their sheaths overlap. Equations (8), (9), and (10) yield the sheath thickness $s_f$, $s_-$, and $s_+$ for voltages near the floating potential, at highly negative probe biases relative to the bulk plasma, and at highly positive probe biases relative to the bulk plasma, respectively (Hutchinson, 2002; Sun et al., 2022):

$$s_f \approx 1.02\lambda_D\left(\left(\frac{1}{2}\ln\left(\frac{m_p}{m_e}\right)\right)^{\frac{1}{2}} - \frac{1}{\sqrt{2}}\right)^{1/2}\left(\left(\frac{1}{2}\ln\left(\frac{m_p}{m_e}\right)\right)^{\frac{1}{2}} + \sqrt{2}\right) \quad (8)$$

$$s_- = 0.79\lambda_D\left(\frac{(e|V_s - V_b|)}{T}\right)^{\frac{3}{4}} \quad (9)$$

$$s_+ = 1.26\lambda_D\left(\frac{(e|V_s - V_b|)}{T}\right)^{\frac{3}{4}} \quad (10)$$

where $\frac{m_p}{m_e}$ represents the mass ratio for an electron-proton plasma and all other variables have been defined previously (Proton-Electron Mass Ratio, 2019). These equations will be used to calculate the probe sheath thicknesses and thus extract the electrode spacing.

# RESULTS

## Mechanical design

Using the plasma density of n ≈ (9 ± 2) x $10^{14}$ $m^{-3}$ measured by DeWit and the constraints set by Equation (5) and (6), the probe geometry was calculated using Equation (7) (DeWit, 2021). The resulting probe has a radius of 0.18 mm and a length of 3 mm. Note that a standard wire gauge of AWG 27 (Φ ≈ 0.36 mm) was used for to simplify manufacturing.
Using Equations (8-10), the Debye length measured by DeWit, and the constraints set by Equations (5) and (6), the electrode spacing $\Delta y$ was calculated to be 55 mm to allow for a factor of safety of 1.2 in the sheath thickness (DeWit, 2021). Note that the sheath lengths calculated from Equations (8) and (10) were summed to extract spacing as the floating probe will be centered between the biased probes, and Equation (10) yielded a larger sheath than Equation (9).

## Electrical design

The chosen electrical design is shown in Figure 3. This circuit measures the current and voltage of the three probes and converts both the current and voltage measurements to 0-5V signals readable by an Arduino's GPIO pins. A low-pass filter was included to avoid aliasing above the Arduino GPIO Nyquist frequency of 5 kHz (Arduino, 2019; DeWit, 2021).

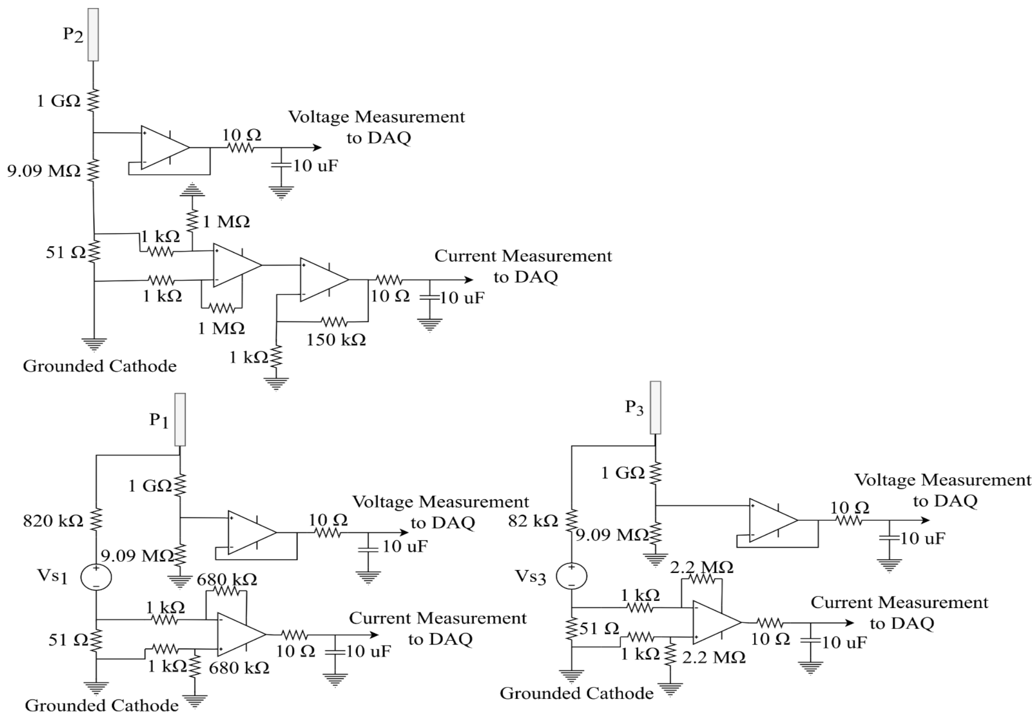


Figure 3 Circuit diagram for the triple probe. $P_1$ represents the positively biased probe, $P_2$ represents the floating probe, and $P_3$ represents the negatively biased probe. These biases are relative to the plasma potential. Each probe has two operational amplifiers which are used in conjunction with resistors to measure the voltage and current of each of the three probes. A current-limiting resistor was used for the three probes to control current influx from the plasma. Voltage dividers were used to attenuate the voltage measurements from the probes to the 0-5V range readable by an Arduino Uno's GPIO pins and extract the probe bias voltage. Current measurement resistors were used to convert the probe voltage into probe current such that it can be plotted on an I-V curve.

A python script utilizing the *PlasmaPy* module was written to extract the signals from the Arduino and re-convert them to the respective voltage and current measurements (*The PlasmaPy Project*, 2023). The I-V curve was extracted by curve fitting the three measured points using Equation (11),

$$I = I_0 + a \ln\left(a + (V - V_0) + \sqrt{1 + (V - V_0)^2}\right), \quad (11)$$

where $I_0$, $V_0$ are translation correction factors and a,b are curve fitting parameters. The plasma parameters were extracted using Equations (12-14).

$$T = \left[\frac{d(\ln I_e)}{dV_b}\right]^{-1} \quad (12)$$

$$n = \frac{I_{sat}}{2er_p d}\left(\frac{m}{2e|V_s - V_b|}\right)^{\frac{1}{2}} \quad (13)$$

$$V_s = V_f + \frac{T}{2e}\ln\left(\frac{2m_p}{m_e}\right) \quad (14)$$

The curve-fitting program was tested using publicly available data, and the results are shown in Table 1 (Pace, 2015). The program extracts plasma parameters within an order of magnitude of the data's reported results, as desired.

| Variable | Expected | Curve Fit Result | Ratio |
|---|---|---|---|
| Electron Temperature, T [eV] | 3.57 | 1.8 | 2 |
| Plasma Density, n [m$^{-3}$] | 8.09e+15 | 9.40e+15 | 0.86 |

**Table 1** Algorithm test results. The program curve fits to Equation (11) and then uses the PlasmaPy python module to extract the plasma parameters from the I-V curve. This data is for a single swept Langmuir probe. Three points were chosen to be curve fit and processed in the analysis: one in the ion saturation region, one in the electron saturation region, and the floating potential point. The data was obtained from David Pace, the Deputy Director of the DIII-D National Fusion Facility, at General Atomics.

# DISCUSSION

## Limitations

DeWit measured collisions within the plasma sheath, however they are not considered in this paper and will need to be evaluated in future work (DeWit, 2021). This can be done by adding correction factors using Modified Talbot-Chou theory (Bose et al., 2017; Tichý et al., 1994). This theory corrects for the additional current draw due to charged particles colliding within the sheath. These collisions reduce the kinetic energy of incoming particles, which enables the probe to collect more particles and thus draw a greater current. Finally, the sensitivity of the signal conditioning circuit is limited for low voltage measurements. Testing should be conducted to see if this sensitivity is sufficient to repeatably measure the plasma parameters to within an order of magnitude of their true value. If this sensitivity is insufficient it is recommended to use instrumentation amplifiers in place of operational amplifiers as they provide better sensitivity for low voltage measurements.

## Conclusions

The purpose of this research was to design a triple Langmuir probe to operate in the Queen's glow discharge device to educate plasma physics at an undergraduate level. The final design is a triple Langmuir probe comprised of two independently biased probes ($P_1$, $P_3$) and an unbiased probe ($P_2$). All probes are 0.18 mm in radius ($r_p$) and have an exposed electrode length of 3 mm (d). The probes are arranged in a vertical line, with the floating probe placed between the two biased probes. Vertical alignment was chosen because it is assumed that the radial variation of plasma parameters is negligible compared to the axial variation of plasma parameters. The probe electrode spacing is 55 mm ($\Delta y$). This spacing ensures the probe sheaths do not overlap, which could cause an electrical arc or introduce errors into the measurement of the plasma parameters. A signal conditioning circuit has also been designed to condition the high voltage signals from the probes to be read by an Arduino Uno. This circuit successfully conditions the high voltage probe signals to a 0-5V signal to be read by the Arduino. The diagnostics tool software has been written to communicate with the Arduino and extract the plasma parameters from the probe signals using equations derived from orbit motion limited (OML) theory.

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# CONFLICT OF INTERESTS

The authors state no conflicts of interest.

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# The Effect of Childhood Victimization on Binge Drinking

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Abstract The purpose of this epidemiological study was to examine the effect of childhood victimization on binge drinking. Although this association is well established in the literature, knowledge of the effects associated with different abuse types is limited. This study used the Statistics Canada General Social Survey, Cycle 28, 2014, which sampled a nationally representative cross-sectional sample of Canadian citizens and permanent residents aged 15 and over living in the provinces and territories (final study sample N = 32,038, 54.3% female, mean age group = 45 to 54). Types of childhood victimization examined in this study were physical abuse, sexual abuse, and witnessing inter-personal violence. Using multiple linear regression analysis, we found that, adjusting for age, sex, marital status, and parental presence in the household, only physical (B = 0.222, 95% CI = 0.135, 0.309, $p < 0.001$) and sexual abuse (B = 0.190, 95% CI = 0.047, 0.323, $p < 0.001$) in childhood predicted higher levels of binge drinking. These findings highlight the need for early identification and treatment of childhood victimization for prevention of alcohol abuse later in life.

## INTRODUCTION

Childhood victimization is defined as all types of violence experienced by a child (Chan, 2019). Childhood victimization includes but is not limited to physical abuse, sexual abuse, emotional or psychological abuse, and neglect occurring before age 18 (World Health Organization, 2010). Recent research showed that one in three Canadians have experienced at least one form of childhood victimization before the age of 15 (Raising Canada, 2021).
Childhood victimization can have adverse lifelong and even intergenerational impacts (Salisbury & Voorhis, 2009). Longitudinal research has reported a relationship between victimization broadly and poor developmental outcomes, including low self-esteem and mental and physical health problems in adulthood (Fergusson et al., 2013; Gilbert et al., 2015). Other studies have shown that childhood victimization is associated with criminal behaviour, substance use problems, and continued victimization throughout the victimized person's life (Werner et al., 2016). Adults who had been physically abused in childhood are more likely to have externalizing or internalizing disorders, low physical health, and to have been convicted of a crime (Lansford et al., 2021). Similarly, adults who had been sexually abused in childhood are more likely to have higher levels of depression, eating disorders, anxiety, and sexual problems, with depression being the most common long-term symptom among survivors (Hall & Hall, 2011). Collectively, this research underscores the public health importance of childhood victimization.

While there is ample evidence supporting the association between childhood victimization and long-term physical and mental health problems (e.g., Fergusson et al., 2013; Gilbert et al., 2015), there is a paucity of research which includes witnessing interparental violence as a form of childhood victimization when examining the association of childhood victimization with alcohol use disorders and binge drinking. This is significant because a growing body of research has documented the harmful impacts of witnessing violence between parents, including low self-esteem and trauma-related symptoms (Edelson et al., 2003) as well as subsequent violent behaviours and aggression (Abrahams & Jewkes, 2005).

Furthermore, most prior research examining childhood victimization as a risk factor for problematic alcohol consumption has focused on alcohol use disorder (AUD), specifically. AUD is an umbrella term which encompasses multiple conditions including alcohol abuse, alcohol dependence, and alcohol addiction (NIAAA, 2021). While AUDs are well-studied, binge drinking is also an important outcome because it is a harmful risk-taking behaviour associated with serious injuries, multiple diseases, and sudden death (Esser et al., 2014). It has also been linked to a higher risk of developing AUD (Esser et al., 2014).

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Previous research findings have shown that age (Bohm et al., 2021), sex (Tavolacci et al., 2019), marital status (Hamplová, 2018), and current parental presence in the household (Mair et al., 2015) are all significantly correlated with binge drinking behaviour. Studying the associations between different childhood victimization types, including witnessing interparental violence, and binge drinking, while controlling for other related variables is an important avenue of research to understand the isolated impact of childhood victimization on binge drinking. A better understanding of this association can inform the practice of clinicians working with persons with childhood victimization experiences, potentially leading to early identification and treatment of those at risk for alcohol use disorders. Several researchers have emphasized the importance of this "trauma-informed approach," which acknowledges the need to understand a patient's life experiences to provide effective care and improve treatment adherence, patient engagement, and health outcomes (Cocozza et al., 2005; Morrissey & Ellis, 2005; Menschner & Maul, 2014).

Motivated by the identified gaps in the literature, the objectives of this study were to determine the prevalence of and characteristics associated with different forms of childhood victimization in Canada and to examine the relationship between childhood victimization and excessive binge drinking.

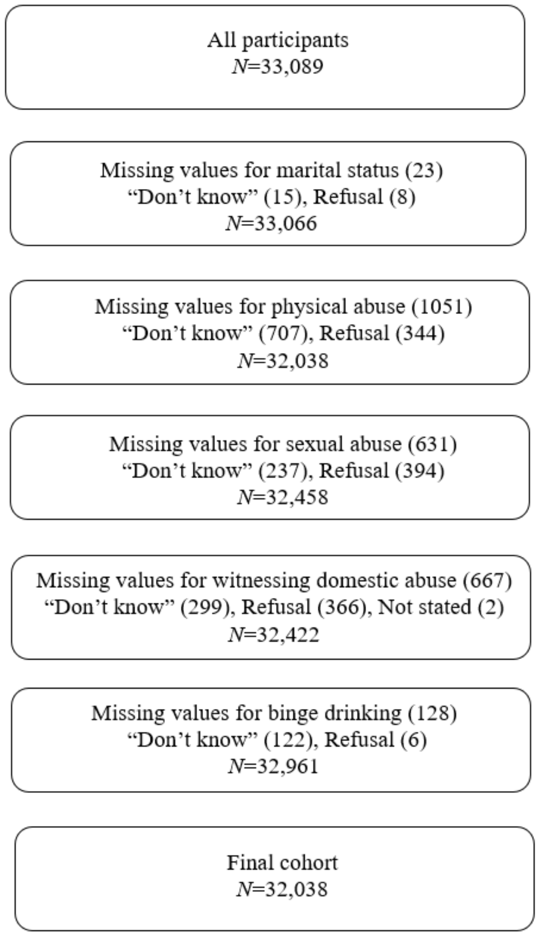


**Figure 1** Missing Data Values (N = 32,038)

## METHODS

### Sample and data source

The data for this study was from Statistics Canada's General Social Survey, Cycle 28 – Victimization (Statistics Canada, 2014). Excluding those with missing data (N = 1,051, representing 3.2% of all respondents), the final analytic sample included 32,038 individuals. The sample represented individuals aged 15 years and older living in private households in Canada and excluded residents of the Yukon, Northwest Territories, and Nunavut as well as full time residents of institutions (Statistics Canada, 2014). The survey was based on a stratified design that employed probability sampling. Survey responses were collected from one randomly selected household member aged 15 or older by using computer assisted telephone interviewing (CATI) technique.

### Measures

*Outcome*. The outcome of interest was binge drinking in adolescence and adulthood (15 years and over). The National Institute on Alcohol Abuse and Alcoholism (2021) defines binge drinking as excessive alcohol use in a short amount of time, corresponding to consumption of 4 or more drinks for females or 5 or more drinks for males in about 2 hours. Like prior studies (e.g., McKetta & Keyes, 2019; Chen et al., 2015), the present study used this definition of "binge drinking." Binge drinking was a continuous variable, captured by asking participants, "How many times in the past month have you had five or more drinks on the same occasion?"

*Exposure*. The main exposure of interest was childhood victimization. Childhood victimization was represented by three different variables: physical assault, sexual assault, and witnessing violence between parents before age 15. Physical assault was assessed by asking respondents, "Before age 15, were you ever physically assaulted by an adult (someone who was aged 18 years or older)?" Experience of sexual assault was measured by asking respondents, "Before age 15, were you ever sexually assaulted by an adult (someone who was aged 18 years or older)?" For both questions, response options were "never", "yes, at least one", "don't know", and "refusal." Witnessing violence between parents was assessed by asking the respondents, "Before age fifteen, how many times did you see or hear any one of your parents, step-parents or guardians hit each other or another adult?" Responses were 1= "never," 2= "one or two times," 3= "three to five times," 4= "six to ten times," and 5= "more than ten times" and treated as numerical data.

*Covariates*. We first ran correlational analyses using the Pearson's correlation coefficient ® and found that age, sex, marital status, and current parental presence in the household were all significantly correlated with binge drinking. Thus, we included these variables in our model as covariates. Age of the respondent at the time of the survey was a seven-level ordinal variable with the categories 15-24 years, 25-34 years, 35-44 years, 45-54 years, 55-64 years, 65-74 years, and 75 years or older. Sex was coded as 0= female and 1= male. Marital status was dummy coded as a binary variable with responses of "married" and "living common law" responses coded as 1 and the responses "widowed," "separated," "divorced," and "single" coded as 0. Finally, the number of the respondent's parents who are currently living in the household was re-coded from 0= "no parents", 1= "one parent", 2= "two parents" to 1= "one or more parents", and 0= "no parents."

## Statistical Analysis

Multivariable linear regression was used to measure the effect of childhood victimization on binge drinking adjusting for potential confounders and predictors of binge drinking, including age, sex, marital status, and current parental presence. All assumptions of multivariable linear regression were met. To test for multicollinearity, we tested for variance inflation factor (VIF) and found that none of the pairwise correlation coefficients between independent variables were high enough (VIF = 1.–5 - 1.12) to raise concerns about multicollinearity among covariates (James at al., 2013). The data also met the assumption of independent errors (Durbin-Watson value = 2.00). Moreover, a histogram of standardized residuals demonstrated that the errors were approximately normally distributed (results not shown). All analyses were conducted using IBM SPSS Statistics (Version 28).

# RESULTS

## Sample characteristics

Table 1 shows characteristics of the study sample. The age of respondents ranged from 15 to 75 years or older. 45.7% of the respondents reported being male and 54.3% reported being female. 7,587 (35.8%) participants reported binge-drinking at least one time in the past month. Of all respondents, 27.4% reported experiencing physical abuse and 9.4% reported experiencing sexual abuse before age 15. While a higher proportion of males (15.3%) than females (12.1%) reported experiences of childhood physical abuse, a higher of proportion of females (7.3%) than males (2.1%) reported being sexually abused before age 15. The proportion of respondents reporting being physically or sexually abused in childhood was lowest among individuals aged 75 or older (1.3%) and 15 to 24 (0.3%), respectively; and highest among respondents aged 55 to 64 (6.3% physically abused, 2.5% sexually abused). Most respondents (88.8%) reported they had not witnessed violence between parents before age 15. Of the 11.2% of respondents who reported witnessing violence between parents before age 15, approximately half were female (7%), and half were male (6%).

Table 1: Descriptive Statistics of Variables in the Analyses (N = 32,038)

| Dependent Variable | N | % |
|---|---|---|
| Binge Drinking (N = 21,210) | | |
| Never | 13623 | 64.20% |
| 1 time | 2963 | 14.00% |
| 2 times | 1907 | 9.00% |
| 3 times | 683 | 3.20% |
| 4+ times | 2034 | 9.60% |
| | | |
| Independent Variables | | |
| 1. Age (years) | | |
| 15-24 | 3958 | 12.00% |
| 25-34 | 3966 | 12.00% |
| 35-44 | 4832 | 14.60% |
| 45-54 | 5585 | 16.90% |
| 55-64 | 6599 | 19.90% |
| 65-74 | 5026 | 15.20% |
| 75+ | 3123 | 9.40% |
| 2. Sex (male) | 15134 | 45.70% |
| 3. Marital Status (married/ common law) | 15085 | 45.60% |
| 4. Parental Presence (yes) | 4273 | 12.90% |
| 5. Physical Abuse (yes; total) | 9075 | 27.40% |
| male (yes) | 5067 | 15.30% |
| female (yes) | 4008 | 12.10% |
| 15-24 (yes) | 886 | 2.67% |
| 25-34 (yes) | 1052 | 3.18% |
| 35-44 (yes) | 1525 | 4.60% |
| 45-54 (yes) | 1816 | 5.48% |
| 55-64 (yes) | 2112 | 6.38% |
| 65-74 (yes) | 1240 | 3.74% |
| 75+ (yes) | 444 | 1.34% |
| 6. Sexual Abuse (yes; total) | 3071 | 9.40% |
| male (yes) | 686 | 2.10% |
| female (yes) | 2385 | 7.30% |
| 15-24 (yes) | 101 | 0.31% |
| 25-34 (yes) | 254 | 0.78% |
| 35-44 (yes) | 469 | 1.43% |
| 45-54 (yes) | 692 | 2.11% |
| 55-64 (yes) | 832 | 2.55% |
| 65-74 (yes) | 546 | 1.67% |
| 75+ (yes) | 177 | 0.54% |
| 7. Witnessing Domestic Abuse | | |
| Never | 28798 | 88.80% |
| 1-2 times | 1644 | 5.10% |
| 3-5 times | 711 | 2.20% |
| 6-10 times | 323 | 1.00% |
| 10+ times | 946 | 2.90% |

## Childhood Abuse and Excessive Binge Drinking

Table 2 presents the standardized and unstandardized coefficients from the multivariable regression analysis. Together, the independent variables explained 5.6% of the variance in frequency of binge drinking (adjusted $R^2 = 0.056$, $p < 0.001$).

Results partially supported our hypothesis. Of the victimization types, experiencing physical and sexual abuse in childhood was associated with a 0.222 (95% CI = 0.135, 0.309, $p < 0.001$) and 0.190 (95% CI = 0.057, 0.323, $p < 0.005$) increase in the number of binge drinking occasions in the past month, respectively. Witnessing violence between parents before age 15 did not significantly predict binge drinking (B = 0.017, 95% CI = -0.033, 0.068, $p = 0.508$).

Table 2: Multiple regression analysis results, (standardized and unstandardized coefficients are reported, N = 21,210) (Adjusted) R-squared = 0.056 F = 176.408 *p < 0.005; **p < 0.001

| Model | B | SE B | Unstandardized beta (B) 95% CI [LL, UL] |
|---|---|---|---|
| 1. Age (years) | -0.242** | 0.013 | [-0.267, -0.217] |
| 2. Sex (male) | -0.947** | 0.039 | [-1.024, -0.870] |
| 3. Marital Status (married/ common law) | -0.433** | 0.041 | [-0.515, -0.351] |
| 4. Parental Presence (yes) | -0.489** | 0.072 | [-0.637, -0.342] |
| 5. Physical Abuse (yes) | 0.222** | 0.044 | [0.135, 0.309] |
| 6. Sexual Abuse (yes) | 0.190* | 0.068 | [0.057, 0.323] |
| 7. Witnessing Domestic Abuse | 0.017 | 0.026 | [-0.033, 0.068] |

# DISCUSSION

Consistent with prior research, females in our sample were more likely to report a history of childhood sexual abuse (e.g., Briere & Elliott, 2003; Dube et al., 2005), whereas males were more likely to report childhood physical abuse (e.g., Thompson et al., 2004). In addition, our findings were consistent with the reports in the literature that early childhood experiences of violence are associated with problematic alcohol use, including excessive binge drinking in adolescence and adulthood (Widom et al., 2010). As expected, physical and sexual violence in childhood significantly predicted more binge drinking in adolescence and adulthood. Individuals who were physically or sexually assaulted by an adult before age 15 reported higher levels of heavy drinking on any given occasion. A similar pattern was found in previous studies, which reported that adolescents who experienced physical or sexual abuse were three times as likely to use substances than those who had not (National Child Traumatic Stress Network, 2008). Others have also observed significant associations between child physical and sexual abuse and problematic alcohol consumption patterns in adulthood, including heavy episodic drinking, alcohol dependence, and alcohol consequences (e.g., Lown et al., 2010; Moran et al., 2004; Shin et al, 2015). This finding might be explained by theories of coping (Lazarus, 1966). When individuals experience psychological stress, they often report increased alcohol consumption and misuse (Keyes et al., 2012). Similarly, among numerous devastating effects of childhood abuse is the increased likelihood to turn to alcohol later in life to manage nightmares, flashbacks, and feelings of rage. Although alcohol can dull the effects of stress, it also increases the risk of experiencing further trauma (National Child Traumatic Stress Network, 2008).

Contrary to the findings of previous studies (see World Health Organization, 2004), we did not find a significant association between witnessing parental violence and binge drinking, possibly due to a small effect size. That is, this study might have been underpowered to detect rare small effects, since very large sample sizes are needed to find small effects in the population (Open Science Collaboration, 2015). Further studies with larger sample sizes, therefore, might be required to examine the relationship between witnessing domestic violence in childhood and binge drinking.

The present study has a few limitations. First, our study included self-reported variables. Social desirability or recall bias could have led to misclassification of exposure, outcome, and covariates, which would have biased our regression estimates. Second, comparisons between our results and other studies are limited by different definitions of 'binge drinking' (i.e., having five or more drinks on the same occasion). Some studies (e.g., Fillmore & Jude, 2011; Pearson et al., 2016) have reported low validity evidence for the 5+ standard drinks per occasion threshold to measure 'binge drinking.'

Results of this study are consistent with prior research linking childhood victimization experiences to binge drinking in later life, while suggesting that different types of victimization can differentially influence binge drinking patterns. Furthermore, our results call attention to the need for further research aimed at understanding the relationship between the response to childhood abuse and elevations in substance intake. Future studies should include studies of interactions between sex, age, childhood abuse, personality types, and excessive alcohol use, and should focus on the overall contribution of variables. Individual differences in coping styles and personality may influence the strategies people develop in the face of trauma to help manage their painful or difficult emotions. Therefore, more studies, particularly those that use qualitative research methods, should consider the potential effects of different coping mechanisms more carefully and evaluate whether they act as moderators between childhood abuse and binge drinking.

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## CONFLICT OF INTERESTS

The author declares no conflicts of interest.

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# Revisiting the Environmental Kuznets Curve Model: Greenhouse Gas Emissions within Canada

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Abstract The change in human behavior from living on the land to living off the land's resources through industrialization, increasing living standards, and rising incomes have been marked by rapidly increasing emissions of greenhouse gasses (GHGs) into the earth's atmosphere. The Environmental Kuznets curve (EKC) hypothesis posits that as income grows, environmental degradation increases until an economy reaches a tipping point, beyond which environmental degradation will decline as income increases (Stern, 2004). This study empirically examines the validity of the EKC hypothesis as applied to Canada's provinces and territories from 1990-2020, using data on GHG emissions and GDP per capita as environmental degradation and income indicators. Overall, the results of this study support the EKC hypothesis at the Canadian level and confirm the results found by previous studies. Confirmation of the EKC indicates that increasing economic growth in Canada's provinces and territories is unlikely to lead to higher greenhouse gas emissions and instead is likely to result in decreasing GHG emissions.

## INTRODUCTION

Climate change is one of the largest global challenges faced by society today (Mikhaylov et al., 2020). Canada's rapid economic development has been marked by a rapid transition from living on the land to utilizing the land's resources through industrialization, thereby increasing incomes, living standards, and rapidly increasing emissions of greenhouse gasses (GHGs) into the earth's atmosphere. The Environmental Kuznets curve (EKC) describes the trade-off between economic growth and environmental degradation (Stern, 2004). The EKC hypothesis posits that in the early stages of economic development, environmental degradation will increase as income rises until it reaches a turning point. At this point, environmental degradation will begin to decrease as income continues to rise, resulting in an inverted U-shaped curve. Therefore, if appropriate policies are taken, economic growth can eventually lead to environmental improvement (Dinda, 2004; Karsch, 2019).

This study builds upon work conducted by Olale et al. (2018), who examined the EKC hypothesis for Canada from 1990 to 2014, using data from 1990 to 2020 for all of Canada's provinces and territories. Through this research project, we will answer the following key question: is the relationship between GDP per capita and GHG emissions per capita within Canada's provinces and territories consistent with the EKC hypothesis? In addition, by comparing our results with those of Olale et al. (2018), we can examine whether recent developments have changed the relationship between economic development and environmental degradation in the Canadian provinces and territories.

## METHODS

### The Environmental Kuznets Curve hypothesis

The EKC hypothesis originates from the Kuznets curve, which was developed by the Russian economist Simon Kuznets (Stern, 2004). Kuznets hypothesized that economic inequality rises and falls as economic development increases (Kuznets, 1955). The concept of the EKC first emerged with a paper by Grossman and Kreuger (1991), which was subsequently popularized by the 1992 World Bank Development Report (Stern, 2004; World Bank, 1992). As shown in Figure 1, the EKC hypothesis posits that an inverted U-shaped curve represents the relationship between different pollutants and income per capita. Therefore, measures of environmental degradation (such as GHG emissions) increase with economic growth, reach a peak, and decrease as economic development advances.

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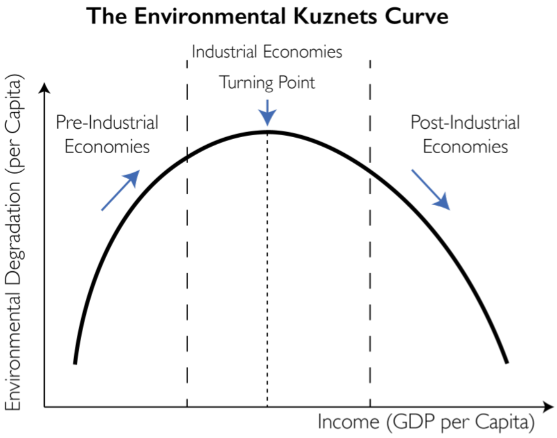


**Figure 1** The EKC Hypothesis: The figure depicts the EKC Hypothesis, where environmental degradation initially increases as income rises, reaching a turning point after which environmental degradation then decreases as income continues to grow.

## Validity of the EKC at a Global, National, and Regional Scale

Contradictory conclusions have been made about the applicability of the EKC on a global scale (Kaya Kanlı & Küçükefe, 2022; Narayan & Narayan, 2010). Some studies use a time series approach to evaluate the EKC within individual countries. In contrast, other studies use a panel data approach where several countries are grouped to test if the EKC holds (Narayan & Narayan, 2010; Uchiyama, 2016). Empirical studies show that the EKC hypothesis does not hold for every single economy or group of economies in the world (Kaya Kanlı & Küçükefe, 2022). This is because the EKC assumes consistent economic development across all countries included in the panel, and panel data analysis imposes strong assumptions on the groups' economic 1growth, which might not represent all countries in the panel (Churchill et al., 2018; Dinda, 2004). analysis of a single country captures country-specific characteristics, such as a country's growth, technological advancements, and policies that affect the relationship between GHG emissions and economic development (Kaya Kanlı & Küçükefe, 2022).

Theoretically, because Canada is in a later stage of economic development, environmental quality should improve as income increases (Dinda, 2004). Several studies find evidence of the EKC in Canada (Ajmi et al., 2015; Hamit-Haggar, 2012; Olale et al., 2018); in contrast, others find that the Canadian relationship between GHG emissions and GDP per capita invalidates the EKC hypothesis (Baek 2015; Day & Grafton 2003; He & Richard, 2010; Kaya Kanlı & Küçükefe, 2022). The Canadian economy varies significantly across the country, and differences in provincial and territorial industrial activities have large implications for GHG emissions (Olale et al., 2018). It follows that the EKC hypothesis in Canada may be better evaluated at the provincial and territorial levels as opposed to the national level.

Given the lack of consensus on studies done at the national level for the EKC hypothesis in Canada, research has been conducted to attempt to identify the cause of these disagreements. Heterogeneity makes the EKC results sensitive to the sample which may result in the differences between the EKC empirical results in cross-country analysis and country-level analysis (Leal & Marques, 2022). Internationally, various methods have been used to examine the EKC with a regional focus, but only two **studies,** Lantz and Feng (2006) and Olale et al. (2018), have studied the EKC at the national and provincial levels in Canada. Therefore, our study contributes to the literature by using more recent data, and by including variables that better capture economic development in the Northwest Territories (NWT) and the Yukon (YK).

## Data & Methodology

This study uses panel data on Canadian provinces and territories from 1990 to 2020. The data[1] consists of 13 panels that include 10 provinces and 3 territories over 30 years, resulting in a total of 385 observations. Data on annual GHG emissions (measured as tonnes of CO2 equivalent) was obtained from Environment and Climate Change Canada, while data on population and GDP was acquired from Statistics Canada (Environment and Climate Change Canada, 2022; Statistics Canada, 2022). Figure 2 displays GDP per capita and GHG per capita from 1990-2020 in all of Canada's provinces and the YK and from 1999-2020 in the NWT and Nunavut (NU). The graphs show the relationship between GHG per capita and GDP per capita in Canada's provinces and territories, which provides some visual evidence consistent with the EKC hypothesis.

[1]Two data sets were used: data set A was used to create Model 1 and Model 3 which excludes data on GHG emissions and GDP from the Northwest Territories (NWT) and Nunavut (NU); data set B was used to create Model 2 and Model 4, which is identical to data set 1 but with the addition of data on the NWT and NU from 1999-2020. This was done because data on NWT and NU from 1990-1998 is unavailable resulting in an unbalanced panel, as well as the mean GDP per capita in NWT not being representative of Canada, possibly influencing results, both were included for transparency.

**GDP per Capita and GHG per Capita in Canada's Provinces and Territories (1990-2020)**

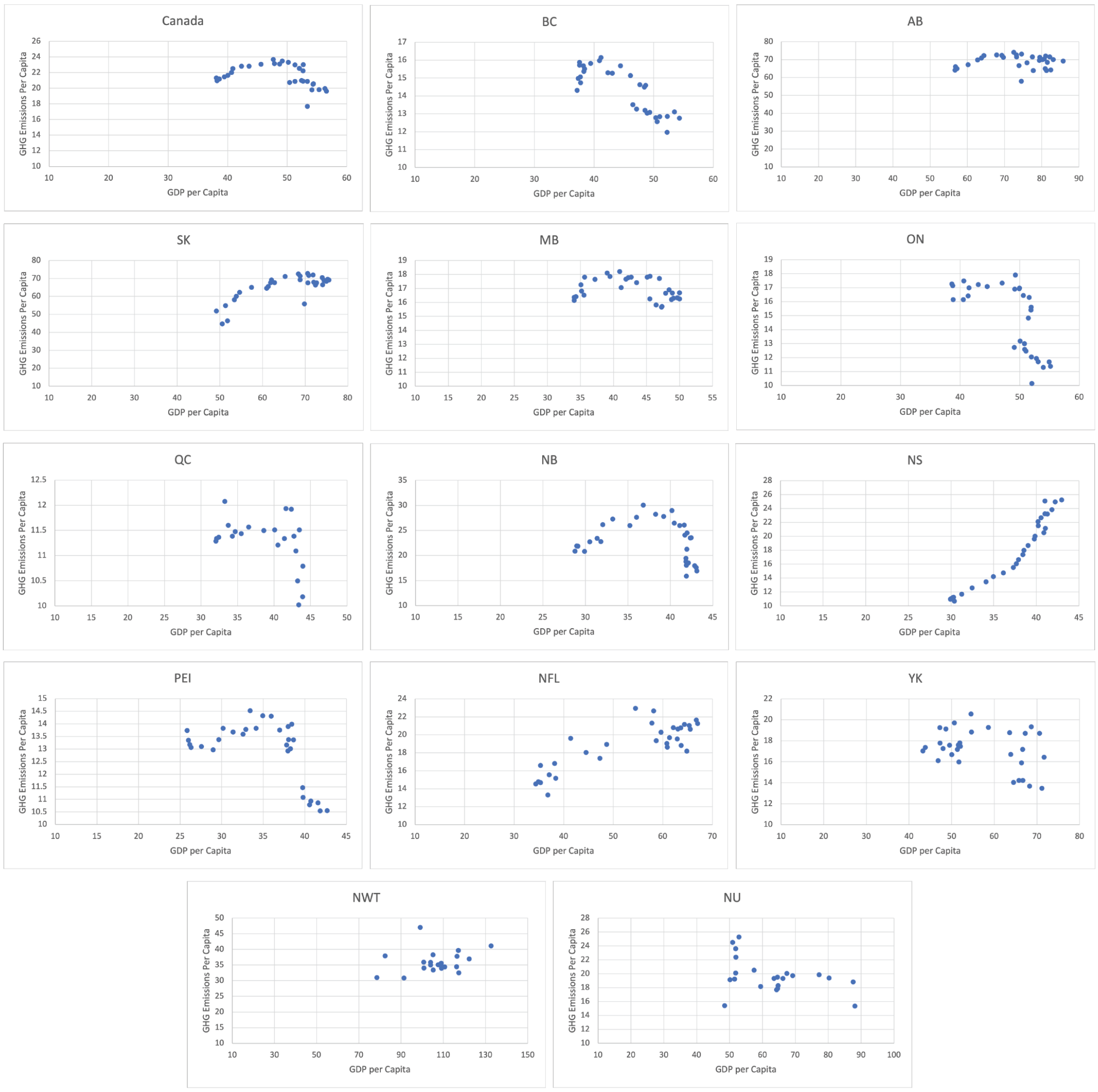


**Figure 2** GDP per Capita and GHG per Capita in Canada's Provinces and Territories (1990-2020): GDP measured in constant 2012 dollars ($000), and GHG emissions are measured in tonnes; both GDP and GHG axes start at 10 units to show better the dispersion of data. Data displayed for NWT and NU is for 1999-2020.

The four models used in this study are adapted from Olale et al.'s (2018) Model 1 specification. The environmental degradation indicator is the dependent variable of GHG emissions per capita. The explanatory variables are GDP per capita (measured in thousands of 2012 dollars) and GDP per capita squared. Each province/territory is represented with a dummy variable in the panel data, and an interactive dummy variable is included that is calculated by multiplying each province/territory dummy by the GDP. This model includes GDP per capita squared to capture the inverted-U shape for the EKC hypothesis. Specifically, we estimate the following model:

$$\frac{GHG\ Emissions_{it}}{Population_{it}} = a_i + \beta_1\left(\frac{GDP_{it}}{Population_{it}}\right) + \beta_2\left(\frac{GDP_{it}}{Population_{it}}\right)^2 + +\delta_i IT_i + \varepsilon_{it} \quad (1)$$

where i indexes the province/territory, t denotes the year, $IT_i$ is an interaction term for GDP and provincial/territorial dummies (interactive dummy variables), $a_i$ is the province/territory intercept, $\beta_1$ and $\beta_2$ are the coefficients to be estimated for our key dependent variables, $\delta_i$ is the coefficient for the interactive dummy variable, and $\varepsilon_{it}$ is the random error term. In accordance with Olale et al. (2018), the EKC hypothesis is supported at the Canadian level if $\beta_1$ is positive, $\beta_2$ is negative, $|\beta_1| > |\beta_2|$, and both coefficients are statistically significant. The EKC hypothesis also holds at the provincial/territorial level if the interactive dummy variable $\delta_i$ for a given province/territory is statistically significant.

Olale et al. (2018) group YK, NWT, and NU into a "Territories" variable. Models 1 and 3 use data from 1990-2020 for all Canadian provinces, including YK, but excluding NWT and NU. Models 2 and 4 use data from all provinces and YK from 1990-2020, including NWT and NU from 1999-2020. Models 1 and 2 are estimated using a pooled regression that constrains the estimated intercept term to be identical across provinces and territories (i.e., $a_i = a$). Models 3 and 4 are estimated using a fixed-effects regression, which permits the estimated intercept term to be unique for each province/territory. This allows exogenous and time-invariant factors unique to each province or territory that may affect GHG in the province/territory to be captured in the intercept. Results in previous studies generally indicate that the fixed-effects specification is the preferred approach (Lantz & Feng, 2006).

## RESULTS

Table 1 summarizes the results of the pooled and the fixed-effects regressions. Our preferred model is Model 3 because Model 1 does not control for fixed effects, and Models 2 and 4 include NWT and NU, which are not representative of the greater Canadian economic and historical context, creating an unbalanced panel that could hurt model fit. Models 1, 2, and 3 all provide support for the EKC hypothesis at the Canadian level, which is indicated by the positive $\beta_1$ estimate, $\beta_2$ negative estimate, $|\beta_1| > |\beta_2|$, and both coefficients being statistically significant. Model 4's $\beta_2$ is statistically insignificant and positive, therefore not supporting the EKC hypothesis at the Canadian level..

**Table 1** Summary of the Regression Results: Values in parentheses represent standard errors; ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. The intercept for the fixed-effects regression includes the province effects.

| Variable | Pooled Regression | | Fixed-Effects Regression | |
|---|---|---|---|---|
| | Model 1 | Model 2 | Model 3 | Model 4 |
| GDP per capita | | 0.390*** | 0.364*** | 0.100*** |
| | -0.11 | -0.069 | -0.055 | -0.029 |
| GDP per capita² | -0.010*** | -0.004*** | -0.024*** | 0.001 |
| | -0.001 | -0.001 | -0.003 | -0.001 |
| BC | -0.098*** | -0.0128*** | 1.391*** | -0.438*** |
| | -0.017 | -0.019 | -0.263 | -0.128 |
| AB | 0.773*** | 0.674*** | 3.055*** | -0.225* |
| | -0.015 | -0.014 | -0.387 | -0.134 |
| SK | 0.765*** | -0.695*** | 2.737*** | -0.153 |
| | -0.013 | -0.014 | -0.322 | -0.123 |
| MB | -0.038** | -0.069*** | 1.394*** | -0.408*** |
| | -0.017 | -0.019 | -0.243 | -0.122 |
| ON | -0.085*** | -0.114*** | 1.824*** | 0.151 |
| | -0.016 | -0.017 | -0.291 | -0.149 |
| QC | -0.185*** | -0.218*** | 2.507*** | 0.829*** |
| | -0.018 | -0.021 | -0.233 | -0.128 |
| NB | 0.132*** | 0.091*** | 1.004*** | 0.107 |
| | -0.02 | -0.022 | -0.217 | -0.092 |
| NS | 0.009 | -0.035 | 1.125*** | 0.107 |
| | -0.021 | -0.023 | -0.222 | -0.098 |
| PEI | -0.126*** | -0.178*** | 1.144*** | 0.017 |
| | -0.022 | -0.025 | -0.204 | -0.113 |
| NFL | 0.036** | -0.013 | 2.583*** | -0.031 |
| | -0.014 | -0.015 | -0.278 | -0.112 |
| YK | -4.850* | -0.051*** | 2.314*** | -0.052 |
| | -2.769 | -0.015 | -0.322 | -0.122 |
| NWT | - | 0.243*** | - | -0.054 |
| | - | -0.021 | - | -0.129 |
| NU | - | 9.799*** | - | -0.079 |
| | - | -2.042 | - | -0.131 |
| Adjusted R² | 0.977 | 0.972 | 0.623 | 0.278 |
| F test: Overall Significance | 1221.164*** | 941.020*** | 44.916*** | 11.645*** |

At the provincial and territorial levels, evidence for the EKC hypothesis differs depending on the estimation method used. Models 1 and 2 use a pooled regression method, and Model 1's interactive dummies are statistically significant at 10% or better in all provinces and territories except for NS. In Model 2, the interactive dummies are statistically significant in all provinces and territories except for NS and NFL. Therefore, these results support the EKC hypothesis in all provinces and territories except for NS in Model 1, and all provinces and territories except for NS and NFL in Model 2. With the fixed effect estimates of Models 3 and 4, the interactive dummies are statistically significant in all provinces and territories in Model 3. However, in Model 4, the only interactive dummies that are statistically significant are BC, AB, MB, and QC, validating the EKC hypothesis only in these provinces.

## DISCUSSION

The results from Model 3 in this study confirm and reflect the results of Model 1 by Olale et al. (2018). Under the pooled regression by Olale et al. (2018), the interactive dummies are statistically significant at 10% or better in all provinces and territories except NB; additionally, the fixed-effects regression done by Olale et al. (2018) finds that all interaction variables are statistically significant. We find that including NWT and NU in the fixed-effects regression model (Model 4) significantly affects the results, with the EKC hypothesis not supported for all of Canada, and the only statistically significant interactive variables being BC, AB, MB, and QC.

The turning point of the EKC is the level of income in which environmental degradation reaches a peak and begins to decline. The turning point is calculated as:

$$\frac{GHG\ Emissions_i}{Population_i} = -\frac{\beta_1+\delta_i}{2\beta_2} \tag{2}$$

Table 2 summarizes the turning point results for this study. The turning points for Model 3 consider all provinces except for QC to be past their turning point. This result differs from Olale et al. (2018) where SK was the only province to have not reached its turning point within the same model parameters. Our contrasting result with SK is likely due to a large increase in GDP per capita in SK in recent years, as there is only a slight change in turning point from the Olale et al. (2018) study. However, our result showing QC not having reached its turning point is the result of the turning point calculation for QC doubling in this study compared to Olale et al. (2018). Models 2 and 4 estimate a relationship that is not the U-shape hypothesized by the EKC, but due to the limitations in the models, will not be focused on in this analysis. Model 1 has turning point estimates that are much lower than those found in Olale et al. (2018). These lower estimates do not reflect the observed behavior of the relationship between GDP and GHG in the provinces and territories of Canada and are symptomatic, which is one of the reasons that fixed effects estimates of Model 3 are preferred for this study.

**Table 2** Turning Point of Annual GDP per Capita ($000)

| Geography | Pooled Regression | | Fixed-Effects Regression | |
|---|---|---|---|---|
| | Model 1 | Model 2 | Model 3 | Model 4 |
| BC | 10.01 | -4.15 | 37.04 | 286.04 |
| AB | 8.58 | -5.14 | 72.15 | 105.64 |
| SK | 9.95 | -3.87 | 65.45 | 44.21 |
| MB | 10.7 | -3.81 | 37.1 | 259.99 |
| ON | 9.94 | -3.86 | 46.18 | -213.01 |
| QC | 10.05 | -3.88 | 60.58 | -786.73 |
| NB | 9.69 | -4.18 | 28.87 | -175.87 |
| NS | 10.18 | -3.83 | 31.43 | -175.79 |
| PEI | 9.81 | -4.06 | 31.83 | -99.4 |
| NFL | 10 | -3.8 | 62.2 | -59.03 |
| YK | 10.15 | -3.9 | 56.53 | -40.78 |
| NWT | - | -4.45 | - | -39.2 |
| NU | - | -4.08 | - | -17.82 |

## CONCLUSIONS

Overall, the results of our study support the EKC hypothesis at the Canadian level and confirm the results found by Olale et al. (2018). As we expected, Model 3 best supports these conclusions, indicative that the inclusion of data from the NWT and the YK within Models 2 and 4 changes the relationship between our relationships of interest. Additionally, the NWT has a significantly higher GDP relative to population density than other provinces, which likely plays a role in our findings.

Under the preferred model, Model 3, all provinces/territories except for QC were found to have a GDP per capita that surpassed the turning point. This suggests that all of Canada's provinces and territories (excluding QC) are past the turning point of the EKC and should have to decrease GHG emissions per capita as GDP per capita increases. The implication of most of Canada's provinces and territories surpassing the turning points is that continued economic growth may be compatible with reducing GHG emissions. Canada's current stage of economic development is advanced and is, therefore, conducive to growth without negatively affecting the environment.

A weakness of this study is that the statistical significance of the provincial interaction variables is taken as the sole confirmation of the EKC in those provinces, and further analysis or interpretation of the magnitude of the regression coefficients, other than the turning point calculations, is not provided. Analysis of this issue is beyond the scope of this study, and further work determining
more robust conditions to assess the validity of the EKC at a provincial and territorial level is recommended as a future research avenue.

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## CONFLICT OF INTERESTS

The authors declare no conflicts of interest.

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