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Key Points:
- Higher school greenness was associated with improved individual-level academic performance in a capital city of the Global South
- Associations of greater magnitude and strength for students in public schools. No significant associations detected in private schools
- Greenness around schools might aid in reducing educational and environmental inequalities in urban areas

Supporting Information:
Supporting Information may be found in the online version of this article.

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School Greenness and Student-Level Academic Performance: Evidence From the Global South

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Abstract Greenspace in schools might enhance students' academic performance. However, the literature—dominated by ecological studies at the school level in countries from the Northern Hemisphere—presents mixed evidence of a beneficial association. We evaluated the association between school greenness and student-level academic performance in Santiago, Chile, a capital city of the Global South. This cross-sectional study included 281,695 fourth-grade students attending 1,498 public, charter, and private schools in Santiago city between 2014 and 2018. Student-level academic performance was assessed using standardized test scores and indicators of attainment of learning standards in mathematics and reading. School greenness was estimated using Normalized Difference Vegetation Index (NDVI). Linear and generalized linear mixed-effects models were fit to evaluate associations, adjusting for individual- and school-level sociodemographic factors. Analyses were stratified by school type. In fully adjusted models, a 0.1 increase in school greenness was associated with higher test scores in mathematics (36.9 points, 95% CI: 2.49; 4.88) and in reading (1.84 points, 95% CI: 0.73; 2.95); as well as with higher odds of attaining learning standards in mathematics (OR: 1.20, 95% CI: 1.12; 1.28) and reading (OR: 1.07, 95% CI: 1.02; 1.13). Stratified analysis showed differences by school type, with associations of greater magnitude and strength for students attending public schools. No significant associations were detected for students in private schools. Higher school greenness was associated with improved individual-level academic outcomes among elementary-aged students in a capital city in South America. Our results highlight the potential of greenness in the school environment to moderate educational and environmental inequalities in urban areas.

Plain Language Summary Vegetation in the school environment might help students learn and perform better in cognitive-demanding tasks. We linked standardized test records of 281,695 students in 1,498 schools in Santiago, Chile with measurements of vegetation around schools derived from satellite data, in order to investigate the association between school greenness and students' academic performance. We found that students who attended schools with more greenery had higher test scores in both mathematics and reading and were more likely to achieve learning standards in these subjects, even after taking into account differences between schools and students' socioeconomic contexts. The study also found that these beneficial associations were more substantial for students attending public schools than for those in private schools. These results highlight the potential benefits of having green spaces in schools, especially for students in urban areas, and suggest that this could be a way to address educational and environmental inequalities.

1. Introduction

The environment where students spend time impacts the way they learn and can have present and future impacts on health and quality of life (Hahn & Truman, 2015). Traditionally, the main focus of research on the factors that influence academic performance in elementary-aged children has been placed on socioeconomic and contextual factors of schools and students, such as school infrastructure, teacher training, household income, and educational attainment of parents (Banerjee, 2016; Barahona et al., 2018; Mizala & Torche, 2012; Valenzuela et al., 2014). However, the physical environment of schools can influence student health and psychological state, modify their behaviors, and therefore, impact their academic outcomes (Tanner, 2009). Building on a well-established body of research on the benefits of contact with nature on children's health, development, and cognitive function, there

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is growing interest in the potential of green space in the school environment to support learning and enhance academic achievement (M. P. Jimenez et al., 2021; Kuo et al., 2019).

Green spaces can influence children's academic performance through multiple pathways. Direct and indirect contact with vegetation can evoke positive changes in psychological state, promote stress recovery, and aid in the replenishment of cognitive resources (Kaplan, 1995; Ulrich et al., 1991). The presence of vegetation in educational environments also promotes positive attitudes toward learning, such as interest and enjoyment in learning, self-discipline, and autonomy (Kuo et al., 2019). Additionally, greenspace can mitigate adverse environmental exposures, such as air pollution, heat, and noise, that have detrimental impacts on students' health, cognitive capacities, and their academic performance (Markevych et al., 2017). Green spaces also provide opportunities to play and interact with peers, as well as opportunities for physical activity, which have been associated with improved cognitive function and greater academic achievement in school children (Carlson et al., 2011). Nevertheless, despite the hypothesized beneficial influence of green spaces on children's learning outcomes, research findings have been inconsistent.

The number of studies exploring the association between green space and academic performance has expanded rapidly over recent years (Browning & Rigolon, 2019). The majority of studies available use ecological designs, analyzing data on outcomes and student characteristics aggregated at the school level. For example, studies in the Northeastern region of the United States reported positive associations between school-level standardized test scores and greenness surrounding schools (Browning & Locke, 2020; Kweon et al., 2017; Leung et al., 2019), as did a study looking at tree cover around public schools in Toronto, Canada (Sivarajah et al., 2018). On the other hand, a study linking school-level outcomes and greenspace around schools in several cities across the U.S. found no evidence in support of a beneficial association (Hodson & Sander, 2019), and two studies even found negative associations (Beere & Kingham, 2017; Browning et al., 2018). Mixed findings have been observed for other academic outcomes, including graduation rates, and attainment of learning standards (Beere & Kingham, 2017; Hodson & Sander, 2021; Kuo et al., 2018).

A potential source of the variation in the observed associations is that ecological studies at the school level are unable to adequately control for individual attributes and contextual factors, given that cultural and socioeconomic backgrounds of students can modify the observed association between greenspace exposure and academic outcomes (Browning & Rigolon, 2019). The influence of students' characteristics and socioeconomic backgrounds on academic performance is well documented in the literature (Banerjee, 2016; Barahona et al., 2018; Mizala & Torche, 2012; Valenzuela et al., 2014). Nevertheless, few studies using individual-level data are available to date. A study in Brazil and another in Oregon, USA reported positive associations between school greenness and student-level academic outcomes (final grades and standardized test scores, respectively), using data from census tract of residence to derive covariates to adjust for students' socioeconomic contexts (Donovan et al., 2018; Requia & Adams, 2022). The only study using student-level outcome and covariate data found no evidence of an association between greenness surrounding schools and final grades of students in Germany (Markevych et al., 2019). As only a limited number of individual-level studies is available, it is not known whether associations observed at the school-level hold true at the student level. Therefore, additional research is needed to understand how individual-level factors might influence this association and help frame existing evidence.

Finally, the majority of studies on school greenspace and academic performance have been conducted in developed countries in North America and Europe (Browning & Rigolon, 2019), with a limited number of school-level studies from the Global South (Requia & Adams, 2022; Requia et al., 2022). Cultural backgrounds can influence perceptions of risks and benefits from urban vegetation and can even modify its relationship with health outcomes (Amano et al., 2018; Ordóñez-Barona, 2017; Riechers et al., 2018; Rigolon et al., 2018). Previous findings also suggest that the association between greenspace and academic performance differs across environmental and sociodemographic contexts (Hodson & Sander, 2021; Kuo et al., 2018, 2021). Thus, the extent to which assumptions and findings from available studies are generalizable to other regions in the world with different cultural and geographic contexts is uncertain. To address these gaps, we leverage satellite observations, standardized test scores records, and data at the individual and school levels to evaluate the association between school greenness and student-level academic achievement in a capital city of the Global South.

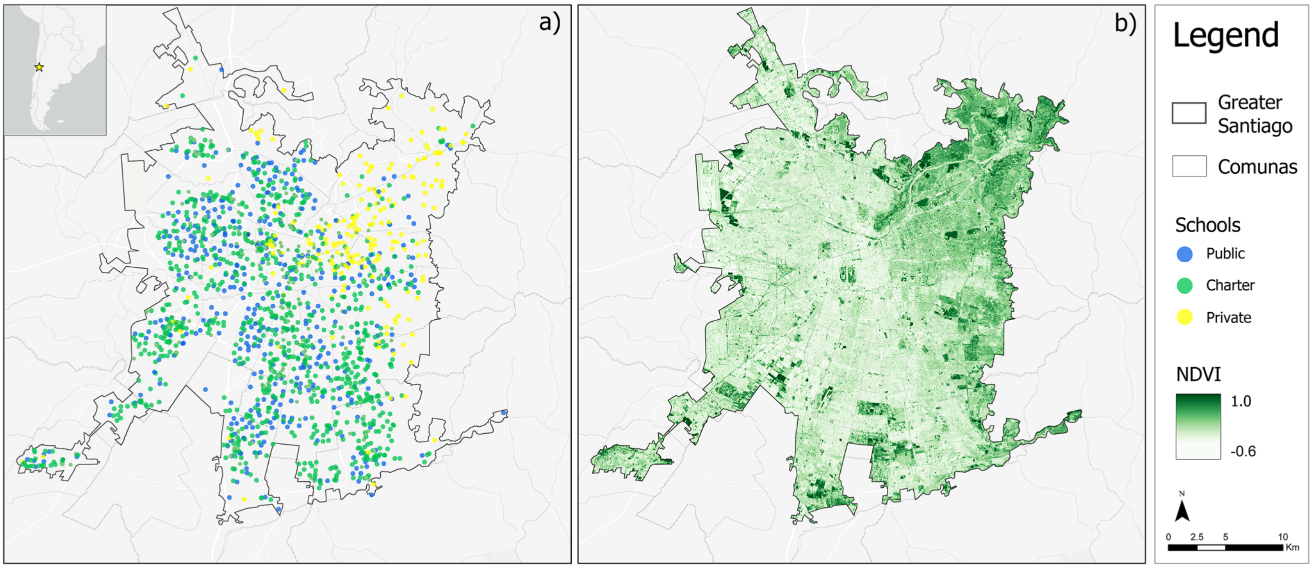

Figure 1. Spatial distribution of schools and greenness in the Greater Santiago (GS). (a) Location of public, private, and charter schools in the GS. (b) Greenness in the GS during the summer season of 2018. Normalized Difference Vegetation Index derived from Landsat 8 data.

2. Data and Methods

2.1. Study Area and Population

This study examines elementary-aged students attending schools within the Greater Santiago (GS), a metropolitan conurbation of 34 Comunas (equivalent to municipalities) around Santiago City, the administrative capital of Chile. Located adjacent to the Andean Piedmont, the GS is home to approximately 35% of the country's population (Instituto Nacional de Estadísticas, 2018). The city has a Mediterranean climate characterized by dry summers and average temperatures of 20°C for the warmest month (January), and 8°C for the coldest month (July). The leaf-on season extends from September to May. Most precipitation occurs during winter, with an average of 312.5 mm of rainfall per year (Escobedo et al., 2016).

The study population consists of fourth-grade students enrolled in private, public, and charter schools within the urban extent of the GS (Figure 1a). In Chile, charter schools are reduced-tuition schools, owned and run privately but receiving a per-student public subsidy. We identified students aged between 9 and 11 years who participated in mathematics and reading standardized tests once during the study period. As a result, students in the fourth grade who were not promoted to the fifth grade within that time frame were excluded from the analysis (n = 331,918). We excluded students without individual-level data on maternal education or household income at the year of test (50,223), who were predominantly male students enrolled in charter schools. Our final sample consisted of 281,695 students enrolled in 1,498 schools within the study area.

2.2. Academic Performance

Academic performance was assessed using student-level standardized test scores in mathematics and reading from a national learning assessment system managed by the Ministry of Education titled Sistema de Medición de Calidad de la Educación (SIMCE). The SIMCE is a battery of tests used to assess students' performance in multiple subjects and determine if they are reaching benchmark learning objectives for their grade level, which has been administered annually to different grades in all schools in Chile since 1998. Specifically, throughout the study period, standardized tests were administered annually to fourth-grade students. However, for eighth-grade students, the tests were only conducted in the years 2014, 2015, and 2017. Binary variables indicating whether the student met or failed to meet learning standards for fourth grade were derived from test scores using subject-specific score cutoffs set by the Ministry of Education. Data was provided by Agencia Chilena de Calidad de la Educación (Ministerio de Educación de Chile, & Agencia Chilena de Calidad de la Educación, 2019).

2.3. Student and School Characteristics

Student- and school-level variables considered for inclusion in our models were selected a priori based on literature investigating the determinants of academic performance in elementary-aged children (Banerjee, 2016; Mizala & Torche, 2012; Valenzuela et al., 2014), as well as previous studies on greenness exposure and academic achievement (Browning & Rigolon, 2019; Donovan et al., 2018; Kuo et al., 2021; Kweon et al., 2017; Leung et al., 2019). Student-level covariates included in our analyses are age at test, sex, annual attendance for the year of test (percent of days in which a student attended school during the academic year), maternal education, and household income at the time the tests were taken. Student-level socioeconomic data were obtained from the SIMCE Parents' Questionnaire, a complementary survey filled by families of students who are taking the tests (~90% completeness). We included the following school-level predictors of academic performance: school type (public, charter, or private), school enrollment (total number of students enrolled at the year of test), and teacher-to-student ratio. School-level attributes and granular data of students were provided by Agencia Chilena de Calidad de la Educación (Ministerio de Educación de Chile, & Agencia Chilena de Calidad de la Educación, 2019). Population density in a 1 km buffer around schools was used as a proxy for schools' urbanicity to account for differences in the intensity of urbanization within the GS, which might influence the association between greenness exposure and academic outcomes (Browning & Locke, 2020; Hodson & Sander, 2021; Markevych et al., 2019). Population density was derived from the Gridded Population of the World (v.4) data product, which provides global 5-year estimates of population density at approximately 1 km^2 resolution (Center for International Earth Science Information Network - CIESIN - Columbia University, 2018).

2.4. School Greenness

School greenness was assessed using the Normalized Difference Vegetation Index (NDVI), a remote-sensing derived metric used to characterize the relative abundance and spatial distribution of ground vegetation. NDVI is widely used to assess greenness exposure in the environmental health literature, as well as in studies linking greenness to academic outcomes (Browning & Locke, 2020; Leung et al., 2019; Markevych et al., 2017, 2019). Using Landsat 8 imagery (30 m spatial resolution) acquired between December 21st and February 28th, we calculated a greenest-pixel composite (i.e., selecting the highest NDVI value registered for each pixel during the specified time window) of the study area for each year between 2014 and 2018. While this time period does not exactly match the academic calendar (students attend school between late February and late December), measuring greenness during top-growth season improves chances of detecting ground vegetation and more accurately characterizing greenness' spatial distribution. Clouds were masked prior to aggregation and negative NDVI values were included in calculations to avoid misclassification of vegetated pixels (R. B. Jimenez et al., 2022). Remote sensing data was accessed and processed in Google Earth Engine (Gorelick et al., 2017). Figure 1b shows the spatial distribution of greenness in the study area. School greenness was quantified as mean NDVI in a 100 m buffer from schools' geocoded addresses to account for students' greenness experience in school yards, schools' surroundings, and classroom views of greenery. School greenness in 250 and 500 m buffers was estimated for scale sensitivity analyses.

2.5. Statistical Analysis

We estimated Spearman's coefficients to understand correlations between variables in our models. We fit Linear mixed effects models (LMM) to evaluate the association between school greenness and standardized test scores, and Generalized Linear Mixed Effects Models (GLMM), to evaluate the association between school greenness and the odds of meeting national learning standards for fourth-grade students. Separate models were fit for mathematics and reading, including the main predictor of interest (school greenness in 100 m buffer), students' age, sex, attendance, maternal educational attainment, and household income, in addition to school type, total school enrollment, school student-to-teacher ratio, and population density around schools. Models were further adjusted by year of test to account for year-to-year differences in applied tests. Random effects for schools and schools' Comuna were included to account for the nested structure of the data. LMM and GLMM were stratified by school type to explore differences across public, charter, and private schools. We estimated variance inflation factors in the overall and stratified models and found no evidence of multicollinearity. Finally, we tested the sensitivity of our results to the choice of school greenness buffer by fitting LMM and GLMM models using school greenness in 250 and 500 m buffers. Statistical analyses were done in the statistical software R using the package *lme4*.

Table 1
Characteristics of the Study Population by School Type (n = 281, 695)

	All schools	Public	Charter	Private
Number of schools	1,498	419	857	222
Number of students	281,695	58,818	184,789	38,088
Female (%)	142,533 (50.6)	28,800 (49.0)	94,306 (51.0)	19,427 (51.0)
Age, years (%)				
9	212,177 (75.3)	42,572 (72.4)	145,268 (78.6)	24,337 (63.9)
10	63,207 (22.4)	13,584 (23.1)	36,113 (19.5)	13,510 (35.5)
11	6,311 (2.2)	2,662 (4.5)	3,408 (1.8)	241 (0.6)
Maternal Education (%)				
Less than High School	62,358 (22.1)	23,695 (40.3)	38,481 (20.8)	182 (0.5)
High School	54,536 (19.4)	13,258 (22.5)	40,548 (21.9)	730 (1.9)
College incomplete	107,205 (38.1)	17,529 (29.8)	81,115 (43.9)	8,561 (22.5)
College complete	10,756 (3.8)	1,563 (2.7)	7,083 (3.8)	2,110 (5.5)
Graduate	46,840 (16.6)	2,773 (4.7)	17,562 (9.5)	26,505 (69.6)
Household Income (%)				
At or below poverty line	113,702 (38.3)	36,467 (62.0)	76,914 (41.6)	321 (0.8)
2x Poverty line	82,583 (29.3)	16,776 (28.5)	64,587 (35.0)	1,220 (3.2)
4x Poverty line	36,493 (13.0)	4,129 (7.0)	28,445 (15.4)	3,919 (10.3)
6x Poverty line	18,653 (6.6)	1,102 (1.9)	10,642 (5.8)	6,909 (18.1)
>6x Poverty line	30,264 (10.7)	344 (0.6)	4,201 (2.3)	25,719 (67.5)
% Attendance (mean (SD))	92.63 (6.13)	90.85 (7.40)	92.72 (5.85)	94.95 (4.14)
School Enrollment (mean (SD))	1,027 (695)	685 (390)	1,100 (747)	1,198 (625)
Student-to-Teacher Ratio (mean (SD))	18.69 (5.37)	15.31 (3.71)	20.84 (4.77)	13.49 (3.82)
School Greenness				
NDVIx10 in 100 m (mean (SD))	2.10 (0.60)	2.02 (0.55)	1.99 (0.49)	2.76 (0.75)
NDVIx10 in 250 m (mean (SD))	2.15 (0.62)	2.04 (0.56)	2.02 (0.48)	2.95 (0.73)
NDVIx10 in 500 m (mean (SD))	2.18 (0.62)	2.06 (0.53)	2.04 (0.47)	3.02 (0.71)
NDVIx10 in 1,000 m (mean (SD))	2.23 (0.60)	2.12 (0.51)	2.10 (0.47)	3.03 (0.69)

3. Results

3.1. Descriptive Analysis

In our sample of 281,695 students (Table 1), the largest proportion was enrolled in charter schools, followed by public and private schools. In general, students in private schools had higher household income, higher maternal educational attainment, were younger in age, and had higher annual attendance compared to those in charter, and public schools, respectively. The sample was balanced between male and female students across school types. In our sample, private schools had the highest school enrollment (total number of students) and were located in more densely populated areas. Charter schools had the highest student-teacher ratio, while the lowest ratios were observed in private schools. In general, private schools had the highest greenness levels, followed by public, and charter schools. Greenness within a 100 m from public and charter schools followed similar distributions, which were different from greenness in private schools. These trends held for greenness in 250 and 500 m buffers (Figure S1 in Supporting Information S1). In general, predictors in all models were moderately correlated (Figure S2 in Supporting Information S1).

Students enrolled in private schools had higher scores in mathematics and reading tests compared to those in charter and public schools (Table 2). The highest proportion of students who achieved learning standards in mathematics and reading was in private schools, and the lowest, in public schools.

Table 2
Descriptive Statistics of Standardized Test Scores and Proportion of Students Meeting or Exceeding Learning Standards in Mathematics and Reading

	Standardized test scores			Meet or exceed learning standards *n* (%)
	Min	Max	Mean (SD)	
All Schools				
Reading	118	383	270.5 (52.1)	183,612 (67.6)
Mathematics	99	381	265.6 (48.2)	193,938 (71.4)
Public Schools				
Reading	119	383	251.9 (52.2)	32,921 (57.8)
Mathematics	99	381	245.7 (48.4)	29,119 (51.2)
Charter Schools				
Reading	118	383	270.6 (50.5)	132,494 (72.2)
Mathematics	101	381	265.8 (46.1)	125,700 (68.5)
Private Schools				
Reading	124	383	302.9 (44.1)	28,523 (90.8)
Mathematics	118	381	300.4 (39.2)	28,793 (91.6)

3.2. School Greenness and Standardized Test Scores

Higher school greenness was positively associated with mathematics and reading standardized test scores, where a 0.1 increase in school NDVI doubled the magnitude of the association with mathematics (3.69 points, 95% CI: 2.49; 4.88) compared to reading scores (1.84 points, 95% CI: 0.73; 2.95). Stratification by school type showed large differences in this association (Table 3). Stratified analysis for both subject tests revealed differences in the overall versus school type-specific association, as well as differences between stratum-specific estimates. In both subjects, school greenness was more strongly associated with test scores for students attending public schools, followed by charter and private schools, albeit confidence intervals overlapped. For mathematics scores, the positive overall association was driven by charter and public schools, as the confidence interval for private schools contained the null. For reading scores, the positive overall association held only for students in public schools, as we did not find significant associations for students in charter or private schools.

3.3. School Greenness and Attainment of Learning Standards

In fully adjusted models, we found a positive association between school greenness and students' odds of attaining learning standards, where a 0.1 increase in NDVI was associated with 20% (95% CI: 12; 28%) and 7% (95% CI: 0.2; 13%) increased odds of meeting mathematics and reading standards, respectively (Table 4). Stratified analysis showed differences between the school type-specific ORs for both subjects, with the largest estimates for students in public schools. The positive overall association observed for mathematics held in public and charter schools, but it was not significant for students enrolled in private schools. For reading standards, the overall association held only for students attending public schools.

3.4. Sensitivity Analysis

In general, the greenspace scale sensitivity analyses yielded similar trends in associations for the overall and stratified analysis for test scores and attainment of learning standards in both subject tests. The overall associations observed for mathematics and reading scores remained positive and significant across the different school

Table 3
Crude and Adjusted Coefficients of the Associations Between School Greenness and Continuous Standardized Tests Scores for Mathematics and Reading

	All		Public		Charter		Private	
Subject	*β*	95% CI	*β*	95% CI	*β*	95% CI	*β*	95% CI
Mathematics								
Unadjusted Model[a]	7.96	6.68; 9.23	3.75	1.21; 6.30	7.47	5.6; 9.35	0.66	−1.48; 2.81
Adjusted Model[b]	3.69	2.49; 4.88	4.93	2.48; 7.38	3.74	1.99; 5.50	1.25	−1.07; 3.56
Reading								
Unadjusted Model[a]	6.92	5.53; 8.30	4.30	1.85; 6.76	5.95	4.05; 7.85	4.05	1.85; 6.26
Adjusted Model[b]	1.84	0.73; 2.95	3.59	1.41; 5.76	0.55	−1.08; 2.18	0.53	−1.68; 2.74

Note. Table shows coefficients for a 0.1 increment in NDVI in 100 m buffer.
[a]Unadjusted model includes school greenness in 100 m buffer and random effects for school and school's Comuna. [b]Adjusted model includes school greenness in 100 m buffer adjusted by sex, age, maternal education, household income, % attendance in year of test, school enrollment, student-teacher ratio, population density around schools, and year of test. Random effects included for school and school's Comuna.

Table 4
Crude and Adjusted Odds Ratio (OR) of the Association Between School Greenness and Student-Level Attainment of Reading and Mathematics Learning Standards

	All		Public		Charter		Private	
Subject	OR	95% CI	OR	95% CI	OR	95% CI	OR	95% CI
Mathematics								
Unadjusted Model[a]	1.38	1.29; 1.49	1.41	1.25; 1.58	1.26	1.15; 1.38	1.12	0.94; 1.33
Adjusted Model[b]	1.20	1.12; 1.28	1.30	1.17; 1.44	1.15	1.06; 1.25	1.07	0.91; 1.25
Reading								
Unadjusted Model[a]	1.22	1.14; 1.30	1.24	1.12; 1.36	1.10	1.02; 1.20	1.10	0.95; 1.26
Adjusted Model[b]	1.07	1.02; 1.13	1.10	1.01; 1.20	1.06	0.98; 1.14	1.02	0.90; 1.16

Note. Table shows ORs for a 0.1 increment in NDVI in 100 m buffer.
[a]Unadjusted model includes school greenness in 100 m buffer and random effects for school and school's Comuna. [b]Adjusted model includes school greenness in 100 m buffer, adjusted by sex, age, maternal education, household income, % attendance in year of test, school enrollment, student-teacher ratio, population density around schools, and year of test. Random effects included for school and school's Comuna.

greenness buffer sizes (Figure S3 in Supporting Information S1). In stratified analyses, the magnitude of the associations for students in private schools increased as the buffer size expanded. However, the uncertainty of estimates also increased and they did not reach statistical significance. Similarly, overall ORs for the attainment of learning standards in both subjects remained greater than one across buffers, with intervals not containing the null (Figure S4 in Supporting Information S1). The odds ratios (ORs) for students in private schools exhibited an increase with buffer size in both subjects, but they did not reach statistical significance.

4. Discussion

We evaluated the association between school greenness and individual-level academic performance in a large sample of elementary-aged students from a capital city in the Global South. We found that increased greenness around schools was associated with higher standardized test scores and higher odds of attaining learning standards in mathematics and reading tests after controlling for individuals' and schools' characteristics. The beneficial association was more pronounced for students in public schools compared to those in charter and public schools in both subjects. Private schools had a significantly higher mean NDVI and did not show significant associations between school greenness and improved academic performance. To our knowledge, this is the first study outside Europe and North America evaluating the student-level association between school greenspace and academic outcomes using individual-level contextual data. Findings of this study add to the body of evidence supporting a beneficial effect of greener school environments on academic performance and, furthermore, extend available evidence to students in different cultural, demographic, and ecological contexts.

Our findings add to the available evidence of a positive association between greenness around schools and school-level academic performance reported in previous studies (Browning & Locke, 2020; Donovan et al., 2018; Kuo et al., 2018; Kweon et al., 2017; Leung et al., 2019; Requia & Adams, 2022; Sivarajah et al., 2018), suggesting that the beneficial associations observed in aggregated analysis hold at the student level. Our results are somewhat in line with findings by Donovan et al. (2018) who reported a positive association for tree cover in residential census tracts and individual-level reading standardized test scores of students of public schools in Portland, Oregon. The authors reported a 2-point increase in reading test scores associated with a 12% increase in tree cover around school. However, unlike our study, they found no associations for mathematics scores or for other types of vegetation cover around school. While Donovan et al. provides a relevant frame to contextualize our findings, our study differs in many ways, of which the most relevant might be the granularity of data used to control for students' sociodemographic backgrounds. We incorporated student-level household variables while Donovan's study relied on census-tract-level information to control for students' contexts. Additional differences in exposure definition (NDVI vs. vegetation cover), study population in terms of age (fourth grade vs. grades third to eight and 11) and demographics (Hispanic vs. predominantly non-Hispanic white population), and study area (semi-arid GS vs. lush vegetation in Portland) might explain the differences with our results.

The observed differences between stratum-specific effect estimates, as well as differences with effect estimates from the main model suggest that school type modified this association. The positive overall associations found for both subject tests were more pronounced for students in public schools and did not hold for students in private schools. As in many regions of the world, private schools in GS are located in greener areas of the city and tend to have higher school greenness levels compared to charter and private schools (Baró et al., 2021). It is possible that the benefits of an additional increase in greenness do not translate to improved academic performance for students in private schools who already experience sufficiently high exposure and score highly on tests.

Contact with green spaces brings numerous benefits for children's health and general well-being. Previous studies have reported pronounced demographic and socioeconomic inequalities in school greenspace (Baró et al., 2021; Fernández et al., 2022) echoing the overarching inequalities in urban green space distribution in cities around the world (Rigolon et al., 2018). Our study suggests that students in public and charter school perceived greater enhancement in academic performance from vegetation in the school environment, consistent with previous evidence suggesting that students from more disadvantaged backgrounds perceive greater benefits from green space (Kuo et al., 2018). Public and charter schools in our study area have less vegetation in their surroundings, worse academic performance, and predominantly serve socioeconomically disadvantaged students, who, in turn, live in areas with lower access to green spaces. Considering the growing evidence on the benefits of school greenspace on student's health and academic performance, and given the substantial amount of time that children spend in school settings, greening interventions in and around schools might help in reducing disparities in access to and time spent in green spaces, as well as disparities in educational outcomes. This is especially relevant in the context of our study area, where persistent socioeconomic inequalities in the educational system have been extensively documented (Barahona et al., 2018; Meckes & Carrasco, 2010; Mizala & Torche, 2012). More so, increased vegetation around schools would bring additional benefits to the broader school community and neighboring communities, helping narrow neighborhood-level inequalities in greenspace access as well. Nevertheless, the decisions of what and where to plant in order to maximize benefits for students in schools are not trivial. They should consider scientific evidence on ecosystem services from different types of vegetation, knowledge of plant species, and their suitability to local conditions, together with the availability of resources that ensure the sustainability of school greening interventions.

4.1. Limitations

The cross-sectional nature of these analyses does not allow us to draw causal conclusions. However, by using individual-level variables to account for students' socioeconomic contexts, our results yield more accurate estimates of the association, furthering available evidence in that direction. While causal evidence is still limited, there is growing consensus on the benefits of green space on children's general health and well-being, as well as a better understanding of the direct and indirect mechanisms through which these benefits are delivered. Considering that adequately managed green space should not be harmful, future studies should consider randomizing greenness treatments to assess causal effects of greenness in schools on academic performance. Our analyses were also limited by our inability to account for greenness exposure outside schools. The use of NDVI to measure greenness around schools has intrinsic limitations as an exposure metric. NDVI does not provide information about greenspace quality, usage, or accessibility, nor discern between types of greenspace or vegetation (i.e., trees, grass, and shrubs), which is essential to elucidate relevant exposure pathways and mechanisms at play in the greenspace-academic achievement relationship. Nevertheless, NDVI is widely used by epidemiologists studying relationships between greenspace and health, including educational outcomes. By providing a harmonized definition of greenness exposure across studies and fields, using NDVI allows for a direct comparison of results between studies and regions of the world. Future research should continue using NDVI alongside additional greenspace metrics to advance the field toward a more comprehensive understanding of the effects of greenspace on academic achievement.

5. Conclusion

Higher school greenness was associated with higher individual-level academic performance among elementary-aged students in a capital city in South America, with greater magnitude and strength of associations for students in public schools. These results are policy relevant as they highlight the potential of vegetation in the school environment to enhance academic performance and moderate inequalities in educational outcomes in the Global South.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The surface reflectance data from Landsat 8, which were utilized to estimate greenness exposure in schools, are accessible through the Landsat 8 Level 2, Collection 2, Tier 1 dataset courtesy of the U.S. Geological Survey via Google Earth Engine (Gorelick et al., 2017) under open access conditions. The administrative data of students, schools, and households used to characterize students' academic outcomes and socioeconomic contexts in this study were made available to researchers through a data sharing agreement with the Agencia Chilena de Calidad de la Educación (Ministerio de Educación de Chile, & Agencia Chilena de Calidad de la Educación, 2019). Data can be requested at https://www.agenciaeducacion.cl.

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