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RESEARCH ARTICLE

Evaluating the impact of a longitudinal, integrated climate change, health, and environment curriculum in undergraduate medical training at Harvard Medical School

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Abstract

Climate change, air pollution, and ecological degradation are defining public health and health equity challenges of our time. Efforts to integrate and evaluate climate change curriculum in medical education is still nascent. Herein, the authors presented findings of a longitudinal evaluation of such curriculum at Harvard Medical School (HMS). Authors designed and administered competency-based and course content-specific pre/post surveys to first-year HMS students to evaluate the impact of the climate change, environment, and health curriculum. Survey development used an adapted Delphi process to solicit feedback from experts at HMS, students, and the Office of Medical Education and included seven-point Likert scale questions (dichotomized and analyzed using Fisher's exact test). Once data saturation was reached, we conducted a thematic analysis to identify key themes and selected illustrative quotes to support each theme. Surveys were administered to the first-year class of 134 HMS students from August 2023 to December 2024. Response rates varied from 21/132 (15.7%) to 119/134 (82.1%). Comparing pre-to post-course responses, competency-based surveys demonstrated statistically significant improvements in 19/20 items (95.0%) and course content-specific surveys showed statistically significant improvements in 20/29 items (69.0%). The vast majority of open-ended responses affirmed the curriculum's value. This study demonstrated that the curriculum significantly improved medical students' self-perceived

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competence in climate-related topics. While statistically significant improvements were observed, results are based on self-reported perceptions and may be subject to response bias due to response rate attrition during the study. No formal validation process was conducted during survey development. As climate and health equity education continues to expand rapidly, often with little standardization, these findings offer insight for other institutions seeking to build measurably impactful curricula, and ultimately prepare medical students to more effectively deliver patient care on a warming planet.

Introduction

Over 230 medical journals and the World Health Organization have declared climate change the defining public health challenge of the 21st century [1,2]. Anthropogenic climate change has placed unprecedented stress on ecological and human adaptation, increasing the risk of crossing irreversible tipping points [3,4]. Climate change is resulting in worsening heatwaves, extreme weather events, disruptions in reliable access to clean water and nutritious foods, geographic redistribution of infectious diseases, and mass human displacement [5]. The health consequences of these impacts span every specialty and health system, with staggering health impacts. In 2021, an estimated 8.1 million deaths globally were associated with exposure to air pollution, largely attributable to fossil fuel combustion [6] and nearly 500,000 deaths globally were associated with exposure to excess heat [7]. According to the National Oceanic and Atmospheric Administration, the years 2023 and 2024 were the two hottest years on record [8]. The burden of climate change will be felt most acutely by those least responsible in the U.S. and around the world. Indeed, lower-income communities, women, the elderly, children, historically marginalized racial and ethnic groups, and individuals with housing insecurity face significant climate related health inequities. They contribute the least to emissions (with the wealthiest one-percent producing as many emissions as the poorest two-thirds of humanity) and simultaneously face both high exposure and limited adaptive capacity to climate hazards [5,9,10].

Climate change not only impacts public health, but also clinical care, including history taking, diagnostic reasoning, patient counselling, and the resilience of the healthcare delivery system itself. For example, in September 2024, Hurricane Helene caused the flooding of an intravenous (IV) fluid manufacturing plant responsible for 60% of the US IV fluid supply. A survey of healthcare providers revealed that 86% experienced IV fluid shortages, with countless health systems forced to alter surgical scheduling and fluid usage protocols [11]. This example highlights a broader trend – climate change made 74% of extreme weather events more likely or more severe, and healthcare systems are struggling to adapt [12].

To effectively address these rapidly evolving health challenges and equip future physicians with the tools they will need, medical schools must integrate climate literacy into its curricula [13]. In recent years, the Association of American Medical

Colleges (AAMC) has called for the integration of climate change and health into medical education [14]. Institutions are heeding its call: 55% of U.S. medical schools reported required climate health topics in 2022, up from 27% in 2020 [15]. Globally, institutions have also documented climate curricular innovation in undergraduate [16–21] and graduate medical education [22–25], as well as in interprofessional health disciplines, including public health and nursing [26–30]. In response to the Accreditation Council for Graduate Medical Education (ACGME)'s feedback, HMS has developed and implemented 7 longitudinal societal themes that enable students to learn about topics of importance through curricular integration across courses [31]. HMS previously described its development of an institutionally recognized, required, longitudinal, integrated Climate Change, Environment, and Health (CCEH) societal theme [19] and accompanying home developed competency framework (Table 1). In that initial descriptive paper by Kline et al, authors describe in depth the process of designing the societal theme and the HMS competency framework, and then mapping each curricular integration to the competencies. It is one of the first and most comprehensive competency-based climate change curricula documented to date [32]. Our curricular framework has 5 core competencies, each of which has associated secondary competencies.

While a few institutions have documented the implementation of climate change content in undergraduate medical curricula, including single-course modules and elective offerings [33], very few have rigorously evaluated the longitudinal impact of such curricula on defined, competency-based outcomes. Prior studies have primarily relied on descriptive accounts or one-time student satisfaction surveys, limiting insight into whether these interventions translate into sustained educational gains. This study addresses this gap by conducting a comprehensive evaluation of the HMS CCEH curriculum from August 2023-December 2024, the first cohort of full implementation into pre-clerkship courses. We assessed CCEH's impact in two ways, by evaluating 1) how the societal theme broadly affected development in capacities enumerated in our competency framework and 2) how specific curricular integrations, including lectures, case-based learning sessions, small group discussions, and preparatory materials, affected student self-reported understanding and confidence regarding climate health topics specific to each course.

Methods

Ethics statement

Our study protocol was reviewed by the HMS Program in Medical Education's Educational Research Committee and deemed exempt from IRB review.

Members of Students for Environmental Action in Medicine (a chapter of Medical Students for a Sustainable Future), the curriculum faculty director, and a member of the HMS Office of Medical Education designed the surveys implemented in this study (Tables A-K in S1 Text). We used an adapted Delphi process to solicit feedback from experts at Harvard Medical School, students, and the Office of Medical Education to iterate and finalize the survey design. A formal survey validation process was not conducted. Two categories of surveys were developed: 1) the "competency-based survey," which assessed broad, longitudinal competency development over time, (Table A in S1 Text) and 2) the "course content-specific survey," which assesses immediate learning of specific topics integrated into specific courses (Tables B-K in S1 Text). The competency-based surveys directly mirrored language in the actual competency framework.

We administered these surveys to first-year undergraduate medical students in the pre-clerkship portion of the curriculum, which is the initial classroom-based portion of standard medical education before students begin clinical work. (entering class of 2023, n = 134). The CCEH curriculum was designed to specifically integrate into each of the pre-clerkship HMS "Pathways curriculum." Pathways is the primary pre-clerkship educational track at HMS. HMS medical students in the "Health, Science, and Technology (HST)" track (a joint program with Massachusetts Institute of Technology) and Harvard dental students enroll in partially overlapping coursework, but do not receive exposure to the full curriculum. As a result, they were not included to participate in this study. Of note, HMS redesigned its pre-clerkship curriculum in AY2023−24, [31] and we adapted our curriculum to maintain its longitudinal, integrated pedagogy in each new course (Table 2).

Table 1. HMS CCEH Societal Theme Core Competencies. Five core competencies and accompanying secondary competencies for the HMS Climate, Environment, and Health societal theme.

Competency Framework:
CORE COMPETENCY 1: Define the pathophysiological mechanisms by which climate change, air pollution and ecological degradation impact human health 1.1: Explain the ways by which climate change impacts human health through environmental exposure pathways including natural disasters/extreme weather, changes in water quality and quantity, food insecurity, heat stress, air pollution, and vector-borne diseases 1.2: Describe the impact of climate change, air pollution, and ecological degradation on health outcomes including cardiovascular, respiratory, reproductive, neurologic, immunologic, psychiatric, oncologic, and infectious disease processes 1.3: Identify risks for disease emergence, especially zoonoses, that arise from ecological degradation in the form of deforestation, land use changes, pollution, and biodiversity loss
CORE COMPETENCY 2: Apply knowledge of climate impacts on human health to the clinical care of patients including prevention, diagnosis, and risk reduction counseling 2.1: Take a clinical history of environmental exposure risks related to occupation, residence, local environmental hazards and indoor pollutants 2.2: Develop clinical prevention and treatment plans for extreme heat and air pollution exposure based upon identification of at-risk patients, including patients with underlying morbidities and inequitable social determinants of health 2.3: Establish plans to address excess burdens of psychiatric disease that arise from climate change influenced extreme weather events such as heat waves, wildfires, more severe hurricanes, and flooding
CORE COMPETENCY 3: Analyze the historical and structural causes of climate change, air pollution and ecological degradation, and describe the ways in which it creates/exacerbates health inequity. 3.1: Explain ways that climate change intersects with structural racism and health equity in the United States (e.g., redlining, heat islands, disproportionately impacted populations, intersecting health challenges, access to adaptive and protective measures) 3.2: Define environmental justice and recognize its importance to climate health solutions 3.3: Describe impacts of climate change on global health inequities (natural disasters/extreme weather, forced migration, political conflict, food security, water scarcity, and sea level rise), including inequitable resource allocation for adaptive responses
CORE COMPETENCY 4: Describe the ways in which the health system contributes to climate change and how healthcare delivery is vulnerable to climate-related events. *By graduation, students will be able to:* 4.1: List ways in which the delivery of healthcare creates greenhouse gas emissions, pollution, environmental toxicants and waste. 4.2: Explain how climate change can interfere with the delivery of healthcare through effects on access to care and impacts on healthcare facilities and supply chains
CORE COMPETENCY 5: Explore roles health professionals and institutions can play in climate solutions. *By graduation, students will be able to:* 5.1 etc Communicate the health and health equity co-benefits of climate solutions to the general public, policy makers and patients and address climate science misinformation 5.2: Identify health system-based interventions that mitigate healthcare greenhouse gas emissions and adapt healthcare delivery to a changing climate

Adapted from Kline MC, Malits JR, Baker N, Shirley H, Grobman B, Callison WÉ, et al. (2024) Climate Change, Environment, and Health: The implementation and initial evaluation of a longitudinal, integrated curricular theme and novel competency framework at Harvard Medical School. PLOS Clim 3(5): e0000412. https://doi.org/10.1371/journal.pclm.0000412

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Data were collected from July 30, 2023 to December 27, 2024. Pre-competency surveys were administered in July 2023 (the beginning of the 2023–2024 academic year), with identical post-surveys delivered at the conclusion of the pre-clerkship curriculum in December 2024 (Table A in S1 Text). Course content-specific surveys were administered throughout the 17-month period, with pre-surveys delivered before the introduction of CCEH content in each course, and an identical post-survey delivered at the end of the course (Tables B-K in S1 Text). Formal data were not collected in

Table 2. HMS CCEH Curricular Integrations (August 2023-December 2024). Overview of Climate, Environment, and Health societal theme integrations across all HMS Pathways pre-clerkship courses, illustrating content integration, format, and associated competencies for each course.

Course	Course Description	Integration content	Integration format	CCEH Core competencies
Introduction to the Profession	Orientation for first-year medical and dental students to teach professionalism and expectations as physicians in training	Advocacy and activism through a climate lens	Lecture, facilitated small group breakout session	1,2,3,5
Foundations	Integrated basic science courses across multiple disciplines, including microbiology	Land use change and malaria	Prep material, Case- Based Learning (CBL) integration	1,2,3
Practice of Medicine	Longitudinal clinical skills course, focused on history-taking, physical exam, clinical reasoning and primary care	Exposure history and heat risk screening tool	Prep materials to be reviewed with preceptor during clinic	2
Integrated Human Pathophysiology I	Gastroenterology and Hematology physiology and pathophysiology course	Hurricanes and waterborne disease	Lecture integration	1
Essentials of the Profession I	Integrated social sciences course including, social medicine and medical ethics	Environmental and global climate justice	Small group discussion materials, optional lectures on climate policy and environmental justice	3,4,5
Integrated Human Pathophysiology II	Cardiology and Pulmonology physiology and pathophysiology.	Air pollution, asthma, and cardiovascular health	Prep video, CBL integration, assessment question	1,2
Professional Development Week*	Intersession focused on self-reflection, enhancing clinical skills and professionalism	Communicating polarizing science topics, like climate change, as physicians	Workshop	5
Integrated Human Pathophysiology III	Nephrology and Endocrinology physiology and pathophysiology	Heat exposure and kidney disease, dialysis access	Prep materials	1,2,3
Immunity and Defense in Disease**	Dermatology, Allergy, Rheumatology, and infectious disease foundational course	Allergic rhinitis and climate change	Prep material, CBL integration	1,2
Mind, Brain and Behavior	Neurology and psychiatry physiology and pathophysiology	Climate change and mental health	Prep video, assessment question	1,2
Bridges	Preparatory course for students prior to entering clerkship year	Healthcare sustainability and waste, heat stress and geriatrics, cardiovascular and respiratory consequences of air pollution	Prep material, CBL integration, assessment questions	1,2,4

* The curricular integration in Professional Development Week was an elective session and we did not collect formal data for this study.

**Immunity in Defense in Disease had curricular integration, but there was a survey delivery error and data were not collected.

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two courses: 1) “Professional Development Week,” due to the elective nature of the CCEH session and 2) “Immunity in Defense and Disease” due to an administrative data collecting error.

Each survey used a seven-point Likert scale ranging from 1) “strongly disagree” to 7) “strongly agree.” Based on standard deviation estimates from a previous cross-sectional curricular survey [19], our power calculation determined a minimum sample size of 18–20 needed for significance (at alpha of.05 and power of 0.80).

To elicit qualitative feedback, competency-based surveys included the question “Is the climate, environment, and health curriculum valuable in medical school? If yes, why? If not, why?” (Table A in S1 Text) Each course specific post-survey asked “Do you have any comments, criticisms, or suggestions about how the climate change content was organized or presented in (course name).” (Tables B-K in S1 Text).

All surveys were administered via email, using the Qualtrics XM 2025 survey platform. Each survey obtained written informed consent by containing the following statement, “ By participating in this survey, you consent to having your

de-identified responses, analyzed solely in the aggregate, used in publications on this curriculum." We protected student confidentiality by not collecting identifying information. Each survey was cross-sectional; we chose to not link pre- and post-survey data to allow for greater flexibility in student cohort participation over our extended 17-month study period.

We analyzed pre- and post-survey data for all survey respondents and dichotomized the pre- and post- data into two categories: "Agree" (somewhat agree to strongly agree) and "Not agree" (somewhat disagree to strongly disagree, and neither disagree nor agree). The resulting contingency tables were analyzed using Fisher's exact test (Tables 3, 4) to determine changes in the proportion of respondents agreeing with statements in each set of pre- and post- survey questions. We considered P values of < 0.05 to be statistically significant. To determine the effect size of the intervention, we calculated Cramer's V on all Fisher's exact test analyses. Interpretation of the Cramer's V coefficient was determined by the degrees of freedom in the Fisher's exact test analysis. We analyzed our data using two-by-two tables (agree and not agree x pre and post intervention), each with just one degree of freedom. In this circumstance, Cramer's V statistics between 0 and 0.10 indicate a small effect, those between 0.10 and 0.30 a medium effect, and V statistics between 0.30 and 0.50 or greater, a large effect. We analyzed statistics for all quantitative items using IBM SPSS Statistics for Windows, (Version 28.0, Armonk, NY: IBM Corp). We used an adapted Braun and Clark's six phase thematic analysis framework [34] to inductively analyze open ended comments when response rate was adequate for analysis. When data saturation was reached, we conducted a thematic analysis to identify key themes and selected illustrative quotes to support each theme. Authors NB and GB familiarized themselves with the responses, generated initial themes independently, met to discuss initial themes, and then redefined themes until both authors were in agreement. Illustrative quotes were selected by NB and GB which conveyed sentiments shared by more than 1 participant.

Results

All surveys achieved response rates sufficient to be adequately powered. Of 134 eligible students, 110 (82.1%) completed the competency-based pre-survey and 52 (38.8%) students completed the competency-based post-survey (Table 3). Response rates during the academic year for the course content-specific pre- and post-surveys ranged from 21 to 117 per survey administration (Table 4). A standardized survey delivery process was used for each course, and the heterogeneity in response rate did not have a clear cause for variability. Every curricular integration listed in Table 2 was fully evaluated with pre-post surveys and detailed in Table 4 with two exceptions. The curricular integration in the course "Professional Development Week" was not evaluated because it was elective. And there was a survey delivery error in "Immunity in Defense in Disease", and thus data was not collected for that integration.

Competency-based survey results

In our curriculum-wide competency-based survey, all 5 primary core competencies and 19/20 (95.0%) survey items showed statistically significant pre-post gains (Table 3). After exposure to the curriculum, a higher proportion of students felt they could: define the pathophysiological mechanisms by which climate change, air pollution, and ecological degradation impact human health (pre-survey: 36/110, 32.7% v post-survey: 48/52, 92.3%; $p < 0.001$, effect size $= 0.557$); apply knowledge of climate impacts on human health to the clinical care of patients including prevention, diagnosis, and risk reduction counseling (pre-survey: 21/110, 19.1% v post-survey: 47/52, 92.16%; $p < 0.001$, effect size $= 0.688$); analyze the historical and structural causes of climate change, air pollution and ecological degradation and describe the ways in which it creates/exacerbates health inequality (pre-survey: 47/111, 42.3% v post-survey: 46/50, 92.0%; $p < 0.001$, effect size $= 0.465$); describe the ways in which the health care system contributes to climate change and how health care delivery is vulnerable to climate-related events (pre-survey: 45/111, 40.5% v 49/51, 96.1%; $p < 0.001$, effect size $= 0.523$); and be prepared to explore roles health professionals and institutions can play in climate solutions (pre-survey: 78/109, 71.6% v post-survey: 45/47, 95.74%; $p = 0.005$, effect size $= 0.272$).

Table 3. Fisher's exact test analysis for competency-based survey results. Overall competency assessment shows significant student survey response changes from two time points (the beginning and the end of academic year) for each of the five core competencies and associated secondary competencies from Table 1.

Survey Question (Mapped Competency)	Responses Pre-survey ("Pre") Postsurvey ("Post") (N)	Aggregate "Agree" number (%)	Percentage point Change (%)	p-Value	Effect Size
Core Competency 1					
*I can define the pathophysiological mechanisms by which climate change, air pollution and ecological degradation impact human health. (Core Competency 1)	Pre (110)	36 (32.70)	59.6	< 0.001	0.557
	Post (52)	48 (92.30)			
I understand the pathways by which climate change affects human health. (1.1)	Pre (110)	60 (54.54)	41.61	< 0.001	0.416
	Post (52)	50 (96.15)			
I understand the breadth of adverse health outcomes exacerbated by climate change. (1.2)	Pre (110)	64 (58.2)	41.8	< 0.001	0.433
	Post (52)	52 (100.00)			
I understand the pathways by which ecological degradation increases the risk for infectious disease emergence. (1.3)	Pre (110)	62 (56.4)	39.75	< 0.001	0.402
	Post (52)	50 (96.15)			
Core Competency 2					
*I can apply knowledge of climate impacts on human health to the clinical care of patients including prevention, diagnosis, and risk reduction counseling. (Core Competency 2)	Pre (110)	21 (19.1)	73.06	< 0.001	0.688
	Post (52)	47 (92.16)			
I feel confident obtaining a basic environmental and occupational history from a patient. (2.1)	Pre (110)	17 (15.5)	80.58	< 0.001	0.763
	Post (52)	49 (96.08)			
I feel comfortable counseling patients regarding prevention and treatment strategies for exposure to extreme heat. (2.2)	Pre (110)	26 (23.6)	64.64	< 0.001	0.605
	Post (51)	45 (88.24)			
I feel comfortable counseling patients regarding prevention and treatment strategies for exposure to poor air quality. (2.2)	Pre (110)	21 (19.1)	60.9	< 0.001	0.581
	Post (50)	40 (80.00)			
I feel comfortable counseling patients regarding prevention and treatment strategies for poor mental health from exposure to extreme weather events. (2.3)	Pre (110)	18 (16.4)	57.6	< 0.001	0.562
	Post (50)	37 (74.0)			
Core Competency 3					
*I can analyze the historical and structural causes of climate change, air pollution and ecological degradation and describe the ways in which it creates/exacerbates health inequity. (Core Competency 3)	Pre (111)	47 (42.3)	49.7	< 0.001	0.465
	Post (50)	46 (92.0)			
I understand the pathways by which climate change can exacerbate racial/ethnic health inequities in the United States. (3.1)	Pre (111)	64 (57.7)	40.3	< 0.001	0.408
	Post (50)	49 (98.0)			
I understand the effects of environmental racism on patients' health. (3.2)	Pre (111)	61 (54.95)	45.05	< 0.001	0.450
	Post (50)	50 (100.00)			
I understand the pathways by which climate change can cause global socioeconomic health inequities. (3.3)	Pre (111)	68 (61.3)	36.7	< 0.001	0.365
	Post (50)	49 (98.0)			
Core Competency 4					
*I can describe the ways in which the health care system contributes to climate change and how health care delivery is vulnerable to climate-related events. (Core Competency 4)	Pre (111)	45 (40.5)	55.6	< 0.001	0.523
	Post (51)	49 (96.1)			
I understand the ways in which the health care sector contributes to air pollution, climate change, and ecological degradation. (4.1)	Pre (111)	46 (41.4)	56.6	< 0.001	0.533
	Post (51)	50 (98.0)			
I understand the ways in which extreme weather events can disrupt health care delivery. (4.2)	Pre (111)	77 (70.0)	24.12	0.007	0.269
	Post (51	48 (94.12)			
Core Competency 5					
*I am prepared to explore roles health professionals and institutions can play in climate solutions. (Core Competency 5)	Pre (109)	78 (71.6)	24.14	0.005	0.272
	Post (47)	45 (95.74)			

(Continued)

Table 3. (Continued)

Survey Question (Mapped Competency)	Responses Pre-survey ("Pre") Postsurvey ("Post") (N)	Aggregate "Agree" number (%)	Percentage point Change (%)	p-Value	Effect Size
I feel comfortable addressing science misinformation and communicating the health co-benefits of climate solutions to those outside the healthcare field. (5.1)	Pre (109)	61 (55.9)	33.7	0.001	0.328
	Post (48)	43 (89.6)			
I feel capable of creating solutions to reduce the health care sectors' reliance on fossil fuels and to bolster climate resilience. (5.2)	Pre (109)	35 (32.1)	48.8	< 0.001	0.439
	Post (42)	34 (80.9)			
I am interested in leading or contributing to climate solutions that promote health equity. (5.2)	Pre (105)	79 (72.5)	21.1	0.127	0.216
	Post (47)	44 (93.6)			

*primary core competency.

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Course content-specific survey results

Surveys of individual courses revealed statistically significant improvements in 20/29 (69.0%) items (Table 4). For instance, after CCEH curriculum exposure in "Introduction to the Profession", a higher proportion of students agreed with the statement, "I understand the main pathways by which climate change affects human health" (pre-survey: 82/132, 62.1% v post-survey: 52/55, 94.5%; $p < 0.001$, effect size = 0.328). After CCEH curriculum exposure in the course "Essentials," a higher proportion of students agreed with the statement, "I understand the historical context of environmental racism" (pre-survey: 4/53, 7.5% v post-survey: 27/31, 87.1%; $p < .001$, effect size = 0.795). After CCEH curriculum exposure in "Integrated Human Pathophysiology 3," there was a higher proportion of students in agreement with the statement, "I feel confident consulting patients regarding medication use in anticipation of extreme heat events" (pre-survey: 5/31, 16.1% v post-survey: 16/26, 61.5%; $p = 0.002$, effect size = 0.469). After the "Bridges" CCEH integration, there was a higher proportion of students in agreement with the statement, "I understand how to sort waste in a hospital setting" (pre-survey: 9/36, 25.0% pre-survey v 31/32, 96.9% post-survey:; $p < 0.001$, effect size = 0.729).

Free-response comments

In the competency-based pre-survey, 77/81 (95.1%) of students reported that the CCEH theme was valuable and 13/15 (86.7%) also affirmed this in the post-survey. Representative student responses are presented in Table 5. Each quote is from a different participant. Data saturation was reached only in the competency-based pre-surveys, and thus was the only survey in which we conducted thematic analysis. Themes included health impacts, medical professionalism/solutions, social importance, adaptation, health equity, social determinant of health. The competency based post-survey had only 15 open field responses, and did not reach data saturation. For these responses, we have provided 5 illustrative quotes in Table 5. In all of the course content-specific post-surveys, there were a total of only five comments, two of which reported there was too much climate curriculum in medical education. A thematic analysis was not done because data saturation was not reached.

Discussion

The impacts of climate change on clinical medicine and healthcare delivery has brought increased attention to the role of medical education in preparing future physicians to care for patients on a warming planet. HMS is one of the first U.S. based medical schools to formally recognize and support a required climate change, environment and health curriculum [32]. Our previous descriptive paper presented a novel competency framework and emphasized the importance of mapping curricula onto this conceptual model [19]. It also highlighted the importance of a pedagogy based on an integrated, longitudinal approach.

Table 4. Fisher's exact test analysis for course content-specific survey results. Course content-specific survey results showing changes in student agreement before and after each individual course integration, demonstrating immediate impact of theme content within individual HMS courses.

Question (I understand…) (Mapped Competency)	Total Responses Presurvey ("Pre") Postsurvey ("Post") (N)	Aggregate "Agree" number (%)	Percentage point Change (%)	p-value	Effect Size
Introduction to the Profession					
… the human-driven causes of climate change. (Core Competency 1)	Pre (132)	117 (88.6)	11.4	0.300	0.191
	Post (55)	55 (100.0)			
… the main pathways by which climate change affects human health. (1.1)	Pre (132)	82 (62.1)	32.4	< 0.001	0.328
	Post (55)	52 (94.5)			
… the ways by which climate change exacerbates health inequities related to structural racism. (3.1, 3.3)	Pre (132)	79 (59.9)	38.3	< 0.001	0.385
	Post (55)	54 (98.2)			
… the various roles by which health care professionals and students can advocate for climate solutions. (5.2)	Pre (132)	61 (46.2)	44.7	< 0.001	0.429
	Post (55)	50 (90.9)			
Foundations					
… the pathways by which climate change and human activity influence the transmissibility of vector-borne diseases. (1.1-1.3)	Pre (68)	59 (86.80)	1.3	0.268	0.019
	Post (42)	37 (88.10)			
… the potential strategies to prevent the spread of vector-borne diseases.(2.2)	Pre (68)	41 (60.3)	34.9	0.042	0.385
	Post (42)	40 (95.2)			
Practice of Medicine					
I feel confident obtaining a basic environmental and occupational history from a patient. (2.1)	Pre (58)	10 (17.2)	79.7	< 0.001	0.765
	Post (32)	31 (96.9)			
… the risk factors for heat-related harms to human health. (1.1, 2.2)	Pre (58)	43 (74.1)	19.6	0.003	0.240
	Post (32)	30 (93.7)			
I feel comfortable counseling patients regarding the risk factors for heat-related harm. (2.2)	Pre (58)	40 (69.0)	31.0	< 0.001	0.371
	Post (32)	32 (100.0)			
Integrated Human Pathophysiology I					
… the association between diarrheal illness and severe storms and flooding. (1.1-1.2)	Pre (37)	28 (75.7)	18.6	0.075	0.259
	Post (35)	33 (94.3)			
Essentials I					
… the historical context of environmental racism. (3.1)	Pre (53)	4 (7.5)	79.6	< 0.001	0.795
	Post (31)	27 (87.1)			
… the goals of environmental justice. (3.2)	Pre (53)	6 (11.3)	75.8	0.001	0.749
	Post (31)	27 (87.1)			
… healthcare providers' responsibility to address the health impacts of climate change. (5.1)	Pre (53)	2 (3.8)	80.1	< 0.001	0.820
	Post (31)	26 (83.9)			
… the gap between countries most responsible for climate change and those most affected by its consequences. (3.3)	Pre (53)	11 (20.8)	69.5	0.002	0.673
	Post (31)	28 (90.3)			
Integrated Human Pathophysiology II					
… the association between fossil fuel consumption, poor air quality, and human health. (1.1-1.2)	Pre (31)	21 (67.7)	20.3	0.620	0.239
	Post (25)	22 (88.0)			
… the pathophysiologic mechanisms of how air pollution exacerbates allergic asthma. (1.2)	Pre (31)	15 (48.4)	43.6	0.051	0.464
	Post (25)	23 (92.0)			
I feel confident identifying the common types of air pollutants that exert major effects on human health. (1.1–1.2)	Pre (31)	7 (22.6)	49.4	0.007	0.494
	Post (25)	18 (72.0)			

(Continued)

Table 4. (Continued)

Question (I understand…) (Mapped Competency)	Total Responses Presurvey ("Pre") Postsurvey ("Post") (N)	Aggregate "Agree" number (%)	Percentage point Change (%)	p-value	Effect Size
I feel comfortable counseling patients regarding methods to reduce their exposure to air pollution. (2.2)	Pre (31)	10 (32.3)	27.7	0.352	0.277
	Post (25)	15 (60.0)			
Integrated Human Pathophysiology III					
… the pathophysiology underlying the relationship between climate change and CKD. (1.2)	Pre (31)	4 (12.9)	71.7	< 0.001	0.717
	Post (26)	22 (84.6)			
… the pathways by which extreme weather events disrupt healthcare delivery. (4.2)	Pre (31)	20 (64.5)	12.4	0.190	0.135
	Post (26)	20 (76.9)			
I feel confident consulting patients regarding medication use in anticipation of extreme heat events. (2.2)	Pre (31)	5 (16.1)	45.4	0.002	0.469
	Post (26)	16 (61.5)			
Mind, Brain, and Behavior					
… the mechanisms by which climate change can impact both mental health disorders and the risk profiles of psychiatric medications. (1.2, 2.3)	Pre (29)	17 (58.6)	36.6	0.049	0.412
	Post (21)	20 (95.2)			
… the effect of extreme heat on both the increasing risk of neuropsychiatric symptoms and the side effects from psychiatric medications. (2.3)	Pre (29)	17 (58.6)	31.9	< 0.001	0.350
	Post (21)	19 (90.5)			
… the growing phenomenon of eco-anxiety. (1.2)	Pre (29)	22 (75.9)	24.1	< 0.001	0.343
	Post (21)	21 (100.0)			
… the relationship between the increased rates of natural disasters and the increased risk of PTSD. (2.3)	Pre (29)	13 (44.8)	45.7	0.058	0.469
	Post (21)	19 (90.5)			
Bridges					
… how air pollution affects respiratory health (1.2)	Pre (36)	36 (100.0)	0	--	–
	Post (32)	32 (100.0)			
I am aware of the healthcare sector's contribution to waste and greenhouse gas emissions. (4.1)	Pre (36)	27 (75.0)	18.7	0.036	0.069
	Post (32)	30 (93.7)			
I am familiar with how climate change increases mental health morbidity and mortality. (1.2, 2.3)	Pre (36)	20 (55.6)	38.1	< 0.001	0.432
	Post (32)	30 (93.7)			
I am aware of which communities are at a heightened risk for heat-related illness. (2.2, 3.1)	Pre (36)	35 (97.2)	2.8	0.342	0.115
	Post (32)	32 (100.0)			
... how to sort waste in a hospital setting. (4.1, 5.2)	Pre (36)	9 (25.0)	71.9	< 0.001	0.729
	Post (32)	31 (96.9)			

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Climate and health education internationally is being advanced via a combination of consensus statements, proposed competency frameworks, and collaborative implementation efforts. Germany has integrated planetary health learning objectives into its national competency-based catalogue of learning objectives for medical education, which includes national examinations [35]. Formation of collaboratives such as the European Network on Climate and Health education, aim to facilitate transnational collaboration across medical schools in developing curricular models [36]. In Australia and Aotearoa New Zealand, health impacts of climate change are being recognized in standards for accreditation [37]. Consensus statements such as those released by the Association for Medical Education in Europe [38] and proposed frameworks such as core concepts for health professionals developed by the Global Consortium on Climate and Health Education [27] are aids in initial implementation, though many of these aforementioned efforts are largely advisory at this stage. Our competency framework represents a published, peer-reviewed, and now longitudinally evaluated implementation, offering a health equity anchored approach that bridges high-level recommendation, and practical curriculum design.

Table 5. Sample Qualitative Comments. Representative student quotes from open-field section of surveys regarding the perceived value of the societal theme in their education.

Competency-Based Pre-Survey **Is climate, environment and health curriculum valuable in medical school? If yes, why? If not, why?**	
Yes	
Theme	**Representative Student Quote**
Medical Professionalism/ solutions	"Yes because it is so essential to human health and it will become increasingly so. We are reaching a stage where climate change is tangibly affecting everyone across the world, and as future healthcare providers it is important for us to be able to respond to the inevitable health challenges we will face as a consequence. Also, as we are at this precipice, it is important to learn the steps we can take to mitigate climate change, which is a major public health issue." Particpant 27
	"This is something that affects human health; as physicians, we have a duty to improve the health of our patients, and a duty to advocate for that which best improves society so as to improve the lives of our patients." Participant 44
	"I believe climate, environmental, and health curriculum will be extremely valuable in medical school as we as future physicians will be utilizing many materials that will directly or indirectly produce waste, of which a large proportion cannot be disposed of in a sustainable or environmentally friendly way. I believe promoting awareness and inspiring future physicians to begin thinking of ways to slowly reduce healthcare waste would be great ways to improving medical school curricula." Participant 68
Health Impacts	"Yes, climate change plays an integral role in human health and the environment in which we live. It is imperative that we acknowledge it." Participant 2
	"Yes! The climate and environment directly affects how our patients live, breathe, and operate in their daily lives. Without understanding the places our patients come from, we cannot become effective physicians and holistically take care of them." Participant 51
	"Climate, environment and health curricula are INVALUABLE in medical school. Climate change directly impacts health and health inequities and thus any curriculum that does not feature this topic is inadequate in my opinion." Participant 59
	"I believe it is essential, as it is linked to healthcare delivery and health outcomes. It is vital for us as medical students to understand how these broader systemic issues affect access to medicine and quality of healthcare." Participant 60
Health Equity	"Absolutely, climate change is a phenomenon that no one is immune to -- regardless of race, gender, socioeconomic status, or zip code. It affects every aspect of our lives, from the economy to healthcare. Only through interdisciplinary efforts can we mitigate the negative effects of climate change on our health and wellbeing, as well as its exacerbation of existing health inequities." Participant 15
	"I believe that a climate, environment, and health curriculum is valuable in medical school because all of these intersect across communities. In fact, climate and environment has direct impacts on human health, often in inequitable ways based on access to resources, socioeconomic status, and geographic segregation. As physicians, we must address these issues if we want to end human suffering." Participant 65
Social Determinants of Health	"Yes. Climate and environment are vital social determinants of health that directly can impact an individual's wellbeing. For instance, the everyday pollutants and environmental risks that people face can cause issues such as respiratory diseases or allergies." Participant 64
	"Environmental factors are a large part of the social determinants of health that shape the well-being of our communities. Increasingly, they need to be taken into account when taking care of patients and communities and that starts in medical school." Participant 80
Adaptation	"Yes, as our world changes, the profession must adapt to the most pressing needs of patients. Climate change will have a massive impact on human health, so it is very relevant!" Participant 10

(Continued)

Table 5. (Continued)

Competency-Based Pre-Survey **Is climate, environment and health curriculum valuable in medical school? If yes, why? If not, why?**	
Social Importance	"Yes, it is one of the most pressing challenges facing humankind and will affect every aspect of life, so is certainly important to cover in medical school." Participant 1
	"Absolutely. Climate change is the single most pressing existential threat to humanity,needless to say, it is the most prominent danger to human health. We must learn about climate change as part of our moral commitment to human health." Participant 78
No	
Theme	**Sample Student quote**
Importance	"It is important to acknowledge because everything is interconnected. However, I don't see its importance in weight because the connection and impact of climate change has yet to be rigorously shown." Participant 14
Importance	"Currently, climate change seems too far removed from traditional medicine to be valuable in medical school. However, I recognized that this is an opinion that may change depending on what I learn in lectures!" Participant 42
Competency-Based Post-Survey Is climate, environment and health curriculum valuable in medical school? If yes, why? If not, why?	
Yes	
"Yes! It is a growing issue that our generation is responsible for combatting in coming years, and the medical field is a huge contributor to climate change and pollution, and it affects our patients!" Participant 4	
"Yes, we are able to influence the impact of the healthcare sector on climate, and we see many patients whose health is affected by climate change." Participant 7	
"Yes, it is vital as climate change is the biggest threat to humanity in the 21st century and healthcare workers have an extremely important role in the fight." Participant 13	
"Yes because it is a huge health crisis" Participant 11	
No	
"Yes but not to this extent in terms of how many hours we spend talking about it. Also, we can all be climate warriors but we should take into account whether all these changes will make real change. Like is arguing with someone about what should be recycled productive when recycled products may not generate less waste than trash?" Participant 15	

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In our 17-month longitudinal evaluation of this curriculum, we had two goals: 1) to determine if our CCEH curriculum supported the development in our defined competencies and 2) to determine how each curricular integration affected student understanding of that specific topic. Our results suggest that the CCEH curriculum had success towards achieving these goals. Competency-based survey data showed wide-ranging and statistically significant improvement in development across the 5 competency domains across nearly all surveyed items. For many items, the improvement was large, as measured by percentage point change and effect size. For instance, at the beginning of the CCEH curriculum, only 15.5% of students agreed with the statement "I feel confident obtaining a basic environmental and occupational history from a patient," while 96.1% agreed after, a 80.6% percentage point increase with an effect size of 0.763. Likewise, in our course content-specific survey data, we found statistically significant improvements in the majority of items studied, with numerous items showing large improvements. For instance, prior to the course "Essentials", only 3.8% of students agreed that they "understood healthcare providers' responsibility to address the health impacts of climate change," while 83.9% agreed with this statement after the course, resulting a 80.1% percentage point increase with an effect size of 0.820. All items that did not achieve statistically significant improvement did nonetheless show pre-post survey gains. Many of these items had a very high baseline score: for example, over 85% of students reported a high degree of understanding the

human-driven causes of climate change and associated impacts on vector borne disease transmissibility in pre-survey data (Table 4). Additionally, high baseline interest in leading climate solutions showed non-significant change ($p = 0.127$). This likely reflects pre-existing motivation among medical students rather than a curricular limitation, underscoring the importance of designing curricula that channel existing interest into actionable competencies and skills. While students demonstrated both high baselines and significant gains in knowledge based climate health pathways and mechanisms, some items assessing clinical readiness, such as counseling patients about air pollution exposure, showed moderate gains that did not reach statistical significance. This pattern suggests that while didactic learning effectively builds foundational knowledge, developing confidence in clinical application may require more immersive pedagogical approaches, such as standardized patient encounters, simulation exercises, or supervised clinical practice opportunities.

Of note, across both competency-based and course content-specific assessments, students appear to have experienced substantial improvement in understanding of both climate change's impact on health equity topics and clinical skills such as obtaining environmental histories and counseling patients about climate-related health risks. Each of these were priority areas for students and faculty who developed this curriculum.

Open-ended comments in the surveys show that students found learning about climate change in medical school important because they 1) wanted to learn about climate related health impacts, 2) believed it was their professional responsibility to understand how it impacted their patients, 3) found intersections between climate change and health equity 4) found intersections between climate change and other social determinants of health, 5) thought it was an issue of social importance, and 6) understood it would help them adapt medical knowledge and clinical skills to the changing health burdens of a warming planet.

Collectively, these data suggest that our pedagogical approach, including curricular structure, competency framework, and content, was effective in curriculum development. Our findings will help us continue to iterate and improve our curriculum at HMS and may be useful to other medical schools who seek to develop similar curriculum.

Our study has several limitations. First, we decided to make pre-post surveys voluntary and unlinked to ensure anonymity and reduce survey burden on students. However, this approach limits our ability to draw conclusions at the individual-student level, and may introduce selection bias and non independence. Second, our reliance on self-reported data presents inherent limitations of subjectivity in medical education research [39]. Furthermore, our study did not assess the impact of specific teaching methods or the depth of content delivered. Additionally, our pre-survey consistently had higher participation rates than our post-surveys. Though this pattern is common in educational research, it could have introduced participation or selection bias if the pool of students who completed the post-surveys were more likely to agree that the curriculum was beneficial. Additional potential sources of bias could include differential engagement across the student body, as well as social desirability bias, even though surveys were anonymized. Survey instruments were developed by faculty experts but without formal validation, which may affect reliability and validity of measurement. In terms of study generalizability, while implementation of such a curriculum framework at less well-resourced institutions may require some degree of adaptation, the growing availability of free online resources [40] and replicable frameworks such as those described herein, combined with student-driven models that leverage motivated learners with appropriate faculty oversight, may help address capacity constraints across institutional settings.

Next steps for climate change education in medical school

Our study addresses an important gap by conducting a longitudinal study on the impact of a competency-based CCEH curriculum. Further longitudinal evaluations of climate change curriculum in medical school is needed. Such scholarship will contribute to a body of knowledge that will enable medical educators to understand best practices in delivering such curriculum and help organizations like the AAMC work towards recommendations on standardized curricular and competency frameworks. Such standardization may help in creating a meaningful approach to integrate climate-informed medical education into schools across the country and establish medical professionalism in this domain. Ultimately, such an

approach can improve the knowledge and skills future physicians need to more effectively care for patients in the midst of this public health crisis.

Additional evaluation approaches can also be utilized in future assessments. For instance, more objective methods such as assessing the impact of curriculum on climate related assessment-based questions and objective structured clinical examinations (OSCEs) may provide additional opportunities for both data collection and student instruction, for example, evaluating a simulated patient presenting with heat illness [41]. Furthermore, longitudinal follow-up of the impact of the CCEH curriculum on clinical practice would aid in evaluating any lasting effects of our preclinical curriculum interventions in relation to Miller's pyramid, as well as measuring impact over student career trajectories [42]. Lastly, as clerkship and graduate medical education show increasing integration of climate change and health topics, [43–46] expansion of education into clinical training, where trainees learn to apply their didactic learning and develop clinical habits, represents a crucial next step in developing physicians prepared to meet climate-related healthcare diagnostic, therapeutic, and healthcare delivery challenges during their careers.

Conclusions

This exploratory evaluation of self reported data suggests that our novel climate change, environment and health curricular theme has improved students' self perceived competence and knowledge in climate related health issues. More studies are needed to further explore the promise of climate change, environment, and health curricula in closing the relevance-preparedness gap in medical education.

Supporting information

S1 Text. Climate Health Curriculum Evaluation Tool. Table A: Competency based survey tool. **Table B**: Course specific survey tool – Introduction to the Profession. **Table C**: Course specific survey tool – Foundations. **Table D**: Course specific survey tool – Practice of Medicine. **Table E**: Course specific survey tool – Integrated Human Pathophysiology 1. **Table F**: Course specific survey tool – Essentials 1. **Table G**: Course specific survey tool – Integrated Human Pathophysiology 2. **Table H**: Course specific survey tool – Integrated Human Pathophysiology 3. **Table I**: Course specific survey tool – Immunology and Defense in Disease. **Table J**: Course specific survey tool – Mind, Brain, and Behavior. **Table K**: Course specific survey tool – Bridges.
(DOCX)

S1 Data. Raw Data.
(XLSX)

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