PRIMARY RESEARCH OBJECTIVE: The primary objective of my PhD research is to formulate novel statistical methods for accurately quantifying uncertainty and variability in life-cycle assessments (LCA), the primary method used to assess embodied carbon (greenhouse gas emissions associated with the production, transport, construction, and end-of-life of building materials). The results of my work will advance LCA research by enabling more robust decision-making, more accurate sensitivity analyses, and enhanced comparability between whole-building LCAs. Academics, practitioners, and policymakers will thus be empowered to more effectively understand, quantify, and ultimately reduce embodied carbon. **Immediate embodied carbon reduction is necessary for curbing the catastrophic effects of the climate crisis, yet the current body of research is severely limited, and few policies or industry standards incorporate embodied carbon into emission reduction strategies.**

JUSTIFICATION: Although whole-building LCA methodology is standardized by an international coalition of technical standard-setting bodies (ISO 14040/14044), there is *considerable* variability in data quality, impact assumptions, and scope. This variability is particularly appreciable for biogenic carbon, the physical carbon that is stored in biological materials such as wood, hemp, and straw. *Negative* biogenic carbon emissions due to carbon storage are treated inconsistently across whole-building LCAs because these assumptions are not standardized. In a five-building case study series, embodied carbon normalized by floor area ranged from -936 to 207 $kgCO_2e/m^2$ when biogenic carbon storage was included in the analysis and 132 to 557 $kgCO_2e/m^2$ when biogenic carbon storage was excluded [1]. Scientists have investigated several approaches to incorporate uncertainty in whole-building LCA, including but not limited to: probability density functions to model building element service-life [2], probability density functions to model manufacturing emissions [3], and more advanced, exhaustive methods that involve conducting a global sensitivity analysis across parameter spaces determined via Latin hypercube sampling [4]. Unfortunately, these modeling practices are not yet standardized or integrated into whole-building LCA. From 2014-2019, 44% of published LCA studies did not mention uncertainty and 36% mentioned uncertainty but did not incorporate it in the analysis [5]. In summary, there is no consensus among available methods to incorporate uncertainty in whole-building LCA, and available methods are seldom incorporated in LCA research. I aim to build upon these available methods by introducing a probabilistic framework to standardize uncertainty characterization in biogenic carbon accounting, enabling better decision-making and comparability between whole-building LCAs.

Objective 1: Literature Review. ***Intent****:* To assess sources of uncertainty and uncertainty characterization methods in scientific literature and industry case studies. ***Methods***: I will conduct a literature review of academic LCA studies, whole-building LCAs, material-specific LCAs, and embodied carbon benchmarks. I will select the most appropriate sources and characterization methods for LCA uncertainty. I hypothesize that Monte Carlo simulation with probabilistic modeling will most accurately characterize emission uncertainty for a linear model like whole-building LCA.

Objective 2: A Probabilistic Framework for Whole-Building LCA. ***Intent:*** To increase the potential for synthesis between data sets for whole-building LCA in academic research and in practice. ***Methods:*** Based on my findings from the literature review, I will develop a statistical framework for classifying, characterizing, and quantifying uncertainty in LCA. I hypothesize that running whole-building LCAs with my proposed probabilistic approach will more accurately model this uncertainty, which will allow me (1) to standardize uncertainty quantification in LCA research and (2) to enable more accurate comparisons and better decision-making.

Objective 3: Standardizing Biogenic Carbon Accounting. ***Intent and background***: Current approaches to biogenic carbon accounting are deterministic and quantify neither uncertainty nor variability that come from widely varying assumptions. *The '0/0 approach'* assumes net carbon sequestration from tree growth balances with end-of-life carbon emissions, and thus, the biogenic carbon storage and its subsequent release are ignored [6]. *The '-1/+1 approach'* considers biogenic carbon as a negative carbon emission during Life Cycle Stage A (the production stage) with carbon released during Life Cycle Stage C (the end-of-life stage) [6]. *Dynamic LCA* relies on the regrowth of biogenic carbon put into a building by accounting for forest rotation periods over a period leading up to or during the building life [7]. *Carbon discounting methods* calculate a net present value of carbon emissions avoided with biogenic carbon storage [8]. *Ton-year accounting* converts the time-value of biogenic carbon storage into a carbon offset equivalent that yields an estimate of negative emissions per ton-year of storage [9]. *In summary*, there is a vital need to formulate an accurate and standardized modeling methodology that properly accounts for the benefits of biogenic carbon storage in buildings while also quantifying variability and uncertainty in the calculation. ***Methods:*** I will formulate stochastic models for biogenic carbon that produce more accurate and consistent whole-building LCA results. I hypothesize that introducing these stochastic models to dynamic LCA will yield the most accurate and descriptive results but will be computationally expensive and difficult to implement for regular use. Therefore, I posit that a stochastic model based on ton-year accounting will yield a viable, but easy-to-implement approach. My proposed method (likely to be stochastic ton-year accounting) will enable practitioners to circumvent end-of-life assumptions for biogenic carbon, which are often the source of significant uncertainty.

INTELLECTUAL MERIT: Despite being a necessary component to solving the climate crisis, embodied carbon reduction is not widely studied in the US. LCA is the primary method used to research, understand, and reduce embodied carbon, but disparate data sets with widely varied assumptions preclude comparison of existing studies and more advanced analysis. With my research, I will steer researchers and practitioners towards a more complete understanding of the most important data needed to describe the total embodied carbon footprint of a building. With support from the National Renewable Energy Laboratory (NREL) and the University of Colorado, Boulder's Center for Research Data & Digital Scholarship, I will elevate the standards for embodied carbon and LCA research.

BROADER IMPACTS: The two most impactful ways to facilitate widespread, effective embodied carbon reduction are (1) establishing embodied carbon benchmarking methodology and (2) disseminating statistically rigorous embodied carbon reduction tools. **Benchmarks:** Designers need science-based embodied benchmarks to inform effective target setting, though none currently exist. These benchmarks must describe expected ranges of embodied carbon per usable floor area and account for variables such as lateral design requirements, building geometry, building type, and soil quality. My research will be integrated with ongoing research in Dr. Srubar's Living Materials Laboratory to establish embodied carbon benchmarking methodology. Our lab group has collaborators at NREL who are particularly interested in integrating this methodology with their analyses of operational carbon (greenhouse gas emissions associated with building energy use). **Embodied carbon reduction tools:** Industry-standard LCA software programs are proprietary and provide conflicting results with ill-constrained uncertainty. *My research will culminate in publishing an open-source, easy-to-implement software package to ensure broad implementation by researchers and practitioners*. I will then distribute my findings through prominent academic and industry organizations (e.g., CLF, AIA, SEI, UNFCCC, USGBC, WGBC).

CONCLUSION: I am uniquely suited to conduct this research because of (1) my first-hand experience with LCA, engineering design work, and computational research, (2) the exemplary leadership I have demonstrated in the embodied carbon space, and (3) my position in a leading embodied carbon research group with important relationships such as that with NREL. My research will elevate the standard for how academic and industry practitioners conduct LCA, which will be essential for more effectively combating the climate crisis. I will ensure the findings of my research are disseminated to salient technical communities and so that they are applied ubiquitously in industry and academia.

[1] TallWood Design Institute *CLT Case Studies* (2020); [2] K. Gouloti et. al., *Building and Environment* (2020); [3] M.A. DeRousseau et. al., *Journal of Cleaner Production* (2020); [4] E. Igos et. al., *The International Journal of Life Cycle Assessment* (2019); [5] N. Bamber et. al., *The International Journal of Life Cycle Assessment* (2020); [6] Hoxha et. al., *Buildings & Cities* (2020); [7] A. Levasseur et. al., *Environmental Science & Technology* (2010); [8] L. Marshall, A. Kelly, *World Resources Institute* (2010); [9] P. Moura Costa, C. Wilson, *Mitigation and Adaptation Strategies for Global Change* (2000)