

# The Role of Statistics in Sustainability Research

Murali Haran<sup>1</sup>, Robert Nicholas<sup>2</sup>, and Klaus Keller<sup>2,3</sup>

<sup>1</sup> Department of Statistics, Penn State University

<sup>2</sup> Earth and Environmental Systems Institute, Penn State University

<sup>3</sup> Department of Geosciences, Penn State University

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Human use of natural resources has enabled tremendous economic growth, but has also negatively impacted ecosystems that sustain human life. The design of sound risk-management strategies hinges on a scientific understanding of the complex ways in which economic choices impact the environment. The example of fossil fuel consumption provides a useful illustration. At present, fossil fuels are often less expensive than renewable energy sources, but there is a trade-off between short-term and long-term costs. This is because fossil fuel combustion releases carbon dioxide, a greenhouse gas that contributes to the warming of the planet through a process first identified by Svante Arrhenius in 1896 [1] and understood in increasing detail through scientific efforts in recent years [2]. Future climate change associated with anthropogenic (human activity-induced) greenhouse warming is projected to carry considerable costs, ranging from impacts on agricultural yields [3] to increased flooding [4] to reductions in labor productivity [5]. Understanding these trade-offs involves building mathematical models to analyze the interplay between our actions, current and future states of the climate, and ways in which climate affects natural and human systems. Mathematics and statistics are central to these analyses.

Mathematical models are quantitative descriptions of complex systems and their interactions. The physical laws governing a process may be translated into mathematical equations to study how that process will behave under different situations. For example, large systems of differential equations are used to describe how the Greenland Ice Sheet will respond to the temperature and precipitation changes caused by anthropogenic greenhouse gas emissions, which in turn informs sea-level projections.

These mathematical models, no matter how sophisticated, are not perfect predictors of the behavior of such enormously complex systems. Such imperfections are one important reason why the predictions are uncertain. This is one of many places where statistics comes in. It is often not enough to make a single “most likely” prediction; rather, it can be crucial to describe the *uncertainties* inherent in our knowledge of these systems. As the statistician G.E.P. Box put it: “All models are wrong, but some are useful.” [6] The statistician A.O’Hagan points out, “Without any quantification of uncertainty, it is easy to dismiss computer models.” [7] When viewed through the language of statistics, it is easier to see how one might use climate models if we are also careful to characterize the uncertainties associated with them. We can then describe *what we know* along with *how uncertain we are* about what we know.

Being well informed about the extent of our knowledge – both what we know and what we do not know – is central to the design of risk-management strategies. Modern statistical methods also provide tools that are useful for combining information from various sources and can therefore

result in a reduction of uncertainty about various aspects of climate change. For example, spatial statistics models can infer temperatures associated with a region where such information may be scarce by combining information from regions that are nearby or similar to it in other ways. Bayesian hierarchical models and Monte Carlo methods can be used to combine information from climate models with observations to draw conclusions about future climates. These conclusions need to account for various uncertainties, including uncertainties about how the climate behaves (uncertainties about the mathematical description of the climate) and potential uncertainties arising from the data collection process.

Answering important questions related to sustainability hence involves a strong collaboration between fields such as climate science, mathematics, and statistics. Statisticians can translate the climate scientists' knowledge into a framework to quantify what the mathematical models and observations together tell us about potential climate change. Such information can also be combined with economic models to analyze the interactions between human behavior, climate, ecosystems, and economics. As such, statistics and mathematics play important roles in climate science, uncertainty quantification, and sustainability analysis.

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