Balancing needs and seeking solutions for a complex changing world
The role of mathematics in addressing issues of sustainability

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The earth provides us with an astonishing variety of resources. In order for humanity to flourish we must balance our human needs, such as those for energy, clean air, fresh water, and adequate food, with the availability of these resources. Moreover, we must do so in a sustainable manner while operating within the complex constraints imposed by the laws of nature. Sustainability involves improving everyone's quality of life, including that of future generations, by reconciling economic growth, social development and environmental protection [1]. These three domains of sustainability are linked one to another in a complex system [2]. Attempts to find solutions in one domain impact other domains so potential solutions involve balancing competing needs. The Millennium Ecosystem Assessment [3] highlights the urgent challenge we face in finding this balance:

> Human activity is putting such strain on the natural functions of Earth that the ability of the planet's ecosystems to sustain future generations can no longer be taken for granted. The provision of food, fresh water, energy, and materials to a growing population has come at considerable cost to the complex systems of plants, animals, and biological processes that make the planet habitable. Nearly two thirds of the services provided by nature to humankind are found to be in decline worldwide. In effect, the benefits reaped from our engineering of the planet have been achieved by running down natural capital assets. In many cases, it is literally a matter of living on borrowed time.

Mathematics contributes in a myriad of important ways to understanding and addressing sustainability challenges. To highlight and honor these contributions, the Joint Policy Board of Mathematics has chosen the Mathematics of Sustainability as the theme of Math Awareness Month 2013.

One starting point from which to examine sustainability is energy. Over the past century fossil fuels have been the core of our energy system and were an important part of raising our standard of living. Mathematical modeling has helped companies identify likely spots for new fossil fuel reserves whether they be on land or under the seas [4]. Modeling has also been applied to forecast future capacities; for example, in 1956 M. King Hubbert [5] modeled oil production with a normal distribution and correctly predicted that U.S. oil production would peak in the early 1970s.

Fossil fuels power our cities and underlie the success of our economic system. Unfortunately fossil fuels are a finite resource that when consumed have the side effect of releasing greenhouse gases, especially carbon dioxide, into the atmosphere and thereby contribute to global warming. The noted French mathematician Joseph Fourier, writing in the 1820s, introduced the notion that the atmosphere could influence the temperature of the Earth [6]. In the 1890s, the Swedish physical chemist Arrhenius [7] used mathematical techniques to predict that as the level of greenhouse gases in the atmosphere rose, the temperature of the planet would increase. Modern scientists use sophisticated mathematical equations and computer simulations to model in more detail the impact of increasing concentrations of greenhouse gases on Earth's climate [8]. The short version of their findings: the climate will change with overall temperatures increasing, more extreme weather events including more powerful storms and drought in many parts of the world, and rising sea levels as warmer temperatures cause glaciers to melt and sea water to expand. The mathematics of climate change was the theme of Math Awareness Month 2009.

The nations of the world are presently trying to mitigate the severity of climate change impacts by reducing the amount of CO2, and other greenhouse gases, that is released into the atmosphere. The notion of a carbon footprint, which aims to quantify how much carbon dioxide a particular activity generates, is an important tool in this work.

In the developed world, we have the economic resources to adapt to some of these impacts. The field of risk assessment uses mathematics to analyze potential impacts and look for ways to reduce the associated risks.

For developing countries, there is a painful irony at play. These countries are "energy poor" and were not the ones using the large amounts of fossil fuels that contribute to climate change. For example, in these countries there are 1.3 billion people without electricity and 2.7 billion people who do not have access to cooking and heating fuel [9]. And they have fewer resources with which to adapt to the impacts of climate change. This situation certainly brings forth ethical and moral questions. Mathematics can contribute to examining these ethical issues by providing ways to quantify disparities; for example the Gini coefficient is a mathematical way to measure how equally a resource is distributed across a population.

To address these inequities, the United Nations Secretary General has initiated a twenty year campaign called Sustainable Energy for All [9] that aims to provide increased access to energy to raise standards of living in developing countries. Economists use mathematics to help develop such plans and then carefully collect and analyze data to track the progress of the initiatives.

There are numerous sustainable energy approaches being developed and implemented including a variety of wind, hydro and solar energy technologies. Mathematical modeling is used in designing efficient turbines [10] and solar cells and, together with weather data, helps engineers figure out promising locations for wind turbines and solar panels. These alternative energies offer the promise of long-term energy supplies with reduced carbon emissions. But mathematical analysis [11] also points out that these types of low intensity energy sources must be spread across large areas if they are to produce the huge amounts of energy our society uses. We must face the difficult issue of where to locate these fluctuating sources of energy and how to efficiently transmit their energy to areas of need.

At present, 50% of the world's population live in cities. This number is predicted to rise to 70% by 2050 [12] so an important aspect of creating a sustainable world will be building sustainable cities. Architects and engineers are developing more energy efficient buildings [13]. Presently buildings account for about 40% of U.S. energy consumption [14]. City planners are looking at the overall systems that support life in a city (transportation, water supplies, storm water management, trash) and considering the benefits of creative green approaches. To prevent future catastrophic flooding, such as occurred during Hurricane Sandy, should New York City build a huge sea wall for protection or revive its coastal wetlands which reduce storm surges naturally? Before deciding which approach to implement, the planners and engineers have to do the math and determine how well the various approaches will work and how much they will cost.

Where will we get the resources to build these cities and to feed their inhabitants? Worldwide, fish stocks provide millions of people with necessary food. We have seen some fish stocks crash due to over-fishing or poorly handled international treaties. Imposing new restrictions or fishing regulations is often controversial, because those changes impact the economy. And yet, if we overharvest the fisheries today, there will be no fish available to feed future generations and no jobs for the fishing industry of tomorrow. Resource management professionals use mathematical models, building on the logistic equation, to determine how best to manage renewable resources like timber and fish, and possibly restore some of the world's fisheries.

Many businesses are joining the sustainability movement, both to save money by running their operations more efficiently and to demonstrate to their customers that they are progressive companies interested in being good corporate citizens. For example, companies are designing their building to meet LEED building standards and are investing in alternative energy. In making these green decisions, the bottom line is an important component. How much will these new approaches cost and how long will they take to pay for themselves, if at all? While not necessarily as sophisticated as the mathematics behind climate change modeling, the mathematics of cost-benefit analysis is an important part of assisting the business world in going green.

We invite you to look at the MAM 2013 theme poster and accompanying theme essays that provide additional insights into the many ways that mathematics contributes to sustainability. We encourage you to get involved in efforts to build a more sustainable society. Mathematics can help bring clarity and insight to the challenges of sustainability, but it will be our individual and collective efforts that determine whether we succeed or fail in meeting these challenges.

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