Final Project
Due 4/27/2018 at **12 pm** on bCourses

1 Introduction

For the final project in E7, you will be creating a Matlab app to help understand and manage climate change mitigation!

You will be coding a Matlab app to represent the Climate Stabilization Wedges developed by Professors S. Pacala and R. Socolow at Princeton University. The description of the wedges framework that follows is adapted from materials provided by the Carbon Mitigation Initiative (CMI) at Princeton.

Pacala and Socolow introduced the idea of stabilization wedges in a 2004 article in *Science* which has dramatically changed the language of climate science and has been cited over 1700 times (Pacala and Socolow, 2004). A key design feature of the wedges is making decisions about carbon-cutting strategies more tractable by providing a simpler framework to work with. This enables better communication about climate science and can aid in policy making and decisions. The researchers also took on the challenge of reaching an even broader audience by creating a role-play game featuring the stabilization wedges.

Currently, the Stabilization Wedges game is played by teams of participants in a classroom or meeting setting. The core purpose of the Wedges game is to convey the scale of effort needed to address the carbon and climate situation and the necessity of developing a portfolio of options. By the end of the exercise, users should understand the magnitude of human-sourced carbon emissions and feel comfortable comparing the effectiveness, benefits, and drawbacks of a variety of carbon-cutting strategies. The users should appreciate that there is no easy or "right" solution to the carbon and climate problem.

For your final project, your task is to write a Matlab app that can be used as an education and policy tool using the Stabilization Wedges framework as its foundation. The challenge is to automate some of the accounting related to the wedges, and to thus enable more sophisticated mitigation solutions. This will enable a wider range of users to adopt the wedges framework in their decision making, including policy makers, scientists, engineers, students etc. In the process, you will exercise your coding skills, learn to design an app, and also learn about climate mitigation approaches, current and future energy technologies, conservation strategies, and the socio-economic decisions that come into these decisions about the future of planet Earth.

We begin with the science "story" which sets the stage for the app you are going to build, and then describe the detailed requirements and design parameters.

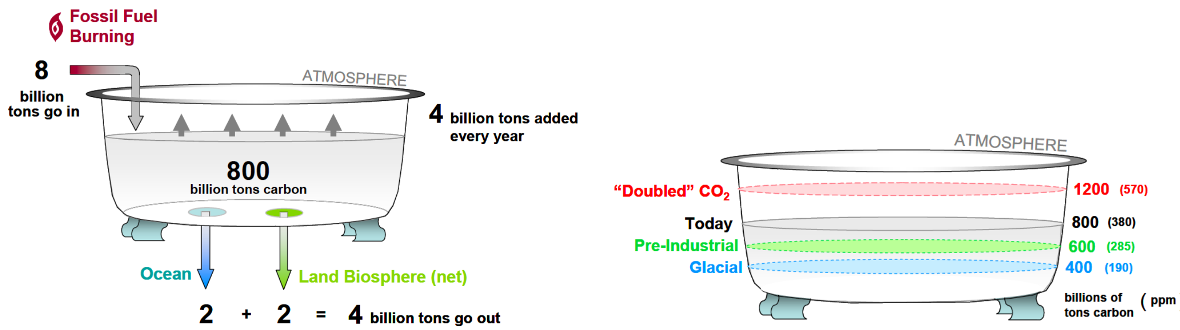

Figure 1: (Left) The atmosphere as a bathtub, with current annual inputs and outputs of carbon. The level in the tub is rising by about 4 billion tons per year. (Right) Past, present (year 2000), and potential future levels of carbon in the atmosphere in two units. 2.1 billion tons of carbon = 1 part per million (ppm). (Current concentrations of carbon dioxide are at about 410 ppm.)

1.1 Carbon and climate - background

Evidence continues to accumulate that carbon dioxide, or CO_2, from fossil fuel burning is causing dangerous interference in the climate. The five warmest years in the global record have all come in the 2010s. The 10 warmest years on record have all come since 1998. Models predict that, without action to curb the growth of greenhouse gases in the atmosphere, we risk triggering catastrophe – cessation of the dominant pattern of ocean circulation, loss of the West Antarctic ice sheet, or a several-fold increase in category-five hurricanes.

CO_2 and some other gases in the atmosphere change the climate by letting sunlight pass through the atmosphere and warm the planet, but hindering the escape of heat to outer space (a phenomenon popularly known as "the greenhouse effect"). By burning fossil fuels, which are composed mainly of hydrogen and carbon, we add CO_2 to the atmosphere.

The Earth's atmosphere contains about 800 billion tons of carbon as CO_2 (as of the year 2000). Combustion of fossil fuels currently adds about 10 billion tons of carbon every year (as of 2017). If we think of the atmosphere as a bathtub, these carbon emissions are like water coming out of the tap to fill the tub (Figure 1). The ocean and land biosphere act as two drains for this bathtub - carbon can be taken out of the atmosphere by being dissolved in the surface ocean or being taken up by growing forests. However, these two "drains" only take out about half the carbon we emit to the atmosphere every year. The remainder accumulates in the atmosphere (currently at a rate of roughly 5 billion tons per year), so the level of carbon in the tub is rising.

The fossil fuel tap was "opened" with the Industrial Revolution. In pre-industrial times, the atmosphere contained only about 600 billion tons of carbon, 200 billion tons less than today (Figure 1, right). As an illustration of the importance of CO_2 to the Earth's climate, ice core records show that past atmospheric carbon changes of a similar magnitude have meant the difference between Ice Ages and the familiar warmer conditions of the past 10,000 years.

Observations indicate that the carbon already added to the atmosphere has raised the global average temperature by around 1° Fahrenheit since the 19th century, and almost every year the fossil fuel tap is opened wider. An average of many forecasts predicts that we'll be adding 16 billion tons of carbon per year to the "bathtub" in 50 years, twice the 2005 rate, unless action is taken to control carbon emissions. If we follow this path (known as "business as usual"), the amount of carbon in the atmosphere will reach 1200 billion tons – double its pre-industrial value - well before the end of this century, and will continue to increase into the future. As a result, the Earth's temperature is expected to rise at a rate unprecedented in the last 10,000 years. How can we get off this path?

1.2 Stabilization wedges - background

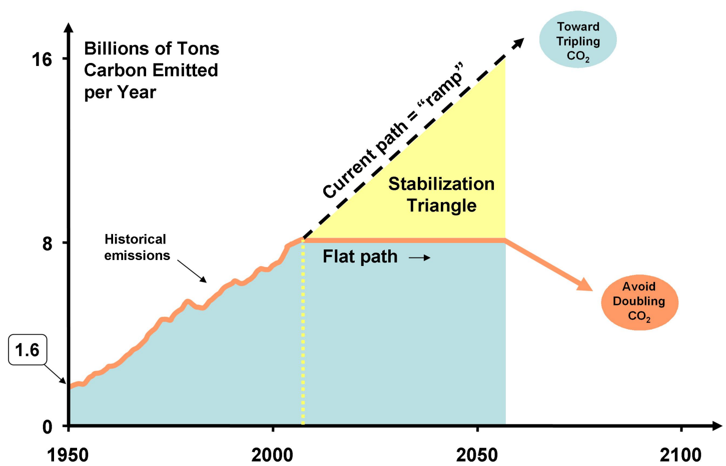

Figure 2: Schematic showing billions of tons of carbon emitted per year and stabilization wedge required to achieve a 'flat path' and avoid doubling CO_2 in the future. Two possible emissions scenarios define the "stabilization triangle" based on 2005 data.

The "stabilization wedges" concept is a simple tool for conveying the emissions cuts that can be made to avoid dramatic climate change.

We consider two futures - allowing emissions to double versus keeping emissions at current levels for the next 50 years (Figure 2). The emissions-doubling path (black dotted line) falls in the middle of the field of most estimates of future carbon emissions. The climb approximately extends the climb for the past 50 years, during which the world's economy grew much faster

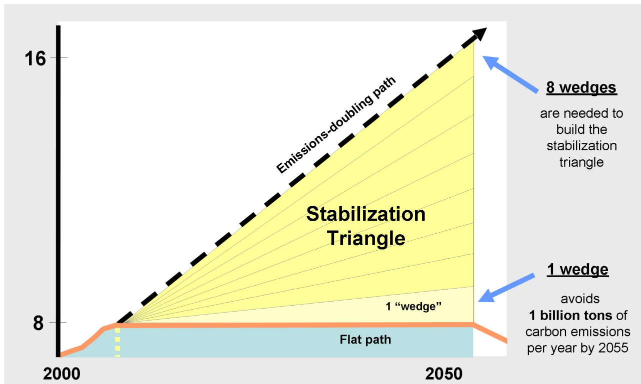

Figure 3: Schematic showing 8 wedges required to build the stabilization triangle based on 2005 data. Each wedges starts from zero and grows until it achieves a reduction of 1 billion tons of carbon emissions in the year 2055. Note: this schematic is for data from 2005!

than its carbon emissions. Emissions could be higher or lower in 50 years, but this path is a reasonable reference scenario.

The emissions-doubling path is predicted to lead to significant global warming by the end of this century. This warming is expected be accompanied by decreased crop yields, increased threats to human health, and more frequent extreme weather events. The planet could also face rising sea-level from melting of the West Antarctic Ice Sheet and Greenland glaciers and destabilization of the ocean's thermohaline circulation that helps redistribute the planet's heat and warm Western Europe.

In contrast, we can prevent a doubling of CO_2 if we can keep emissions flat for the next 50 years, then work to reduce emissions in the second half of the century (Figure 2, orange line). This path is predicted to keep atmospheric carbon under 1200 billion tons (which corresponds to about 570 parts per million (ppm)), allowing us to skirt the worst predicted consequences of climate change.

Keeping emissions flat will require cutting projected carbon output by about 8 billion tons per year by 2060, keeping a total of $\sim$200 billion tons of carbon from entering the atmosphere (see yellow triangle in Figure 3). This carbon savings is what we call the "stabilization triangle."

The conventional wisdom has been that only revolutionary new technologies like nuclear fusion could enable such large emissions cuts. There is no reason, however, why one tool should have to solve the whole problem. CMI set out to quantify the impact that could be made by a portfolio of existing technologies deployed on a massive scale.

To make the problem more tractable, we divided the stabilization triangle into eight "wedges" (Figure 3). A wedge represents a carbon-cutting strategy that has the potential to grow from zero today to avoiding 1 billion tons of carbon emissions per year in 50 years. The wedges can represent ways of either making energy with no or reduced carbon emissions (like nuclear or wind-produced electricity), or storing carbon dioxide to prevent it from building up as rapidly in the atmosphere (either through underground storage or biostorage).

Keeping emissions flat will require the world's societies to "fill in" all the wedges of the stabilization triangle. In CMI's analysis, at least 15 strategies are available now that, with scaling up, could each take care of at least one wedge of emissions reduction. No one strategy can take care of the whole triangle – new strategies will be needed to address both fuel and electricity needs, and some wedge strategies compete with others to replace emissions from the same source – but there is already a more than adequate portfolio of tools available to control carbon emissions for the next 50 years.

1.3 Wedge strategies currently available

There are 15 well-researched strategies already available that could be scaled up over the next 50 years to reduce global carbon emissions by 1 billion tons per year, or one wedge. They are grouped into four major color-coded categories as seen in Figure 4. You can find more details about each wedge and the calculations that go into it in the Appendix.

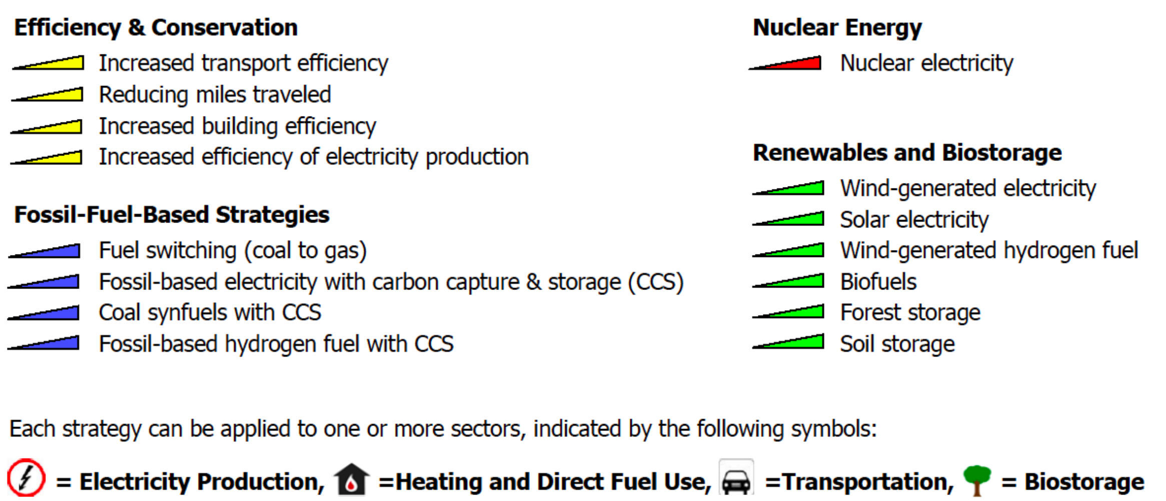

Figure 4: Graphic of the 15 wedges from the Stabilization Wedges game, with their colors by category.

1.4 Estimating global mean temperature increase from carbon emissions

This section will describe a way to find an approximate increase to global mean temperature based on carbon emissions. Note: this approach is based on a very simplified model which makes a lot of assumptions, but will be adequate for our purposes.

Given a certain carbon emissions rate, we can use simple models to make rough approximations for CO_2 concentrations and associated warming. Begin with an equation to describe the change in the total amount of carbon in the atmosphere:

$$\frac{dC}{dt} = E(t) - S(t, C) \tag{1}$$

where C is the mass of carbon in the atmosphere, E is the rate that carbon is being added to the atmosphere (the emission rate) and S is the rate that carbon is leaving the atmosphere (the sink). This equation is exactly correct if $E(t)$ and $S(t, C)$ are defined broadly and accurately enough. This equation states that "the rate of change of carbon in the atmosphere is equal to the rate that carbon is added to the atmosphere minus the rate that carbon is removed from the atmosphere." It's another way of saying that the level in the bathtub (see Figure 1) is increasing at the rate determined by how much is being input and how much is drained (by the ocean and biosphere).

In reality, the sink is a function of many factors; here, we make a simplification that half of all emissions are absorbed, or $S = 0.5E$. This represents the idea that the two "drains" take out about half the carbon we emit to the atmosphere every year, referring again to the bathtub analogy used above. With this simplification made, our model becomes

$$\frac{dC}{dt} = 0.5E(t). \tag{2}$$

The emissions rate will depend on what mitigation strategies (or wedges) are implemented. The "business as usual" scenario can be described with a model for a yearly carbon emission rate (without any mitigation strategies) which doubles every $T = 50$ years beginning from $t_0 = 2017$:

$$E(t) = E_0 \times 2^{\frac{(t-t_0)}{T}}, \tag{3}$$

where E_0, the approximate emissions rate for the year 2017, is equal to 10 GtC/yr (billion tons per year). This curve falls approximately in the middle of the different emissions projections made by the IPCC (Intergovernmental Panel on Climate Change).

To integrate Equation 2 and solve for $C(t)$, we perform a numerical integration using the finite-difference approximation

$$C(t + \Delta t) = C(t) + \Delta t(0.5E(t)). \tag{4}$$

This equation states that "the mass of carbon at the new time is equal to the mass of carbon at the current time plus 0.5 times our current approximate emissions rate multiplied by the time interval." We will use $\Delta t = 1$ year here and approximate the total carbon in the atmosphere at each year, beginning with an initial value of $C(2000) = 800$ GtC in the year 2000, using the historical emission data for years 2000 – 2017 and our modeled emissions for years 2018 – 2068 (this will include any reduction from the wedges!).

Finite differences are a very powerful tool in engineering and physical simulations to numerically integrate equations that cannot be analytically integrated, and are the basis for many numerical methods. The smaller we make Δt the more accurate this method becomes, and the closer it becomes to the true derivative value.

With Eq. 4 we can approximate the mass of carbon in the atmosphere at any year. We can then convert this to CO_2 concentration, using the approximation that 2.1 GtC = 1 ppm CO_2, i.e. 2.1 gigatonnes of carbon emitted to the atmosphere increases the atmospheric CO_2 concentration by 1 ppm. Details of this conversion follow:

(1) Total dry mass of the earth's atmosphere: 5.1×10^{18} kg

(2) Average molecular weight of air in the atmosphere: 29

(3) Atomic weight of carbon: 12

Dividing (1) by (2), the atmosphere (excluding water vapor) contains 1.8×10^{17} kg-moles of gas, and one part per million (by volume) contains 1.8×10^{11} kg-moles of gas. Multiplying by input (3), each part per million (ppm) of molecules containing carbon has a carbon mass of 2.1×10^{12} kg, or 2.1 billion metric tons (Gt). Therefore 1 ppm = 2.1 GtC (Socolow and Lam 2007).

Now we need to convert an increase in CO_2 ppm to an increase in global mean temperature. First we will estimate the increase in radiative forcing from pre-industrial CO_2 levels, ΔF, using the simple relationship

$$\Delta F = 5.35 \ln\left(\frac{\mathrm{CO_2}}{\mathrm{CO_{2,ref}}}\right), \tag{5}$$

where $\mathrm{CO_{2,ref}} = 278$ ppm is the pre-industrial CO_2 level. Once we have ΔF (W/m^2), we relate this to temperature change with

$$\Delta T = \lambda \Delta F, \tag{6}$$

where ΔT is the 'warming' or increase in global mean temperature from the pre-industrial era and λ is the "climate sensitivity parameter." A commonly used estimate is $\lambda = 0.7$°C per W/m^2, though this is a simplified model and subject to debate.

2 Your task

You are tasked with writing a Matlab app for the Stabilization Wedges framework so it can be used to play an enhanced wedges game and design climate mitigation strategies. The app will determine the carbon emissions reductions over a 50 year period based on user input and also compute global CO_2 concentration and temperature increase.

For this project you will work as a team of 3 software engineers (groups of 2 only if necessary). Your team must consist of students in your lab section. You are allowed to write code together for this and only this assignment. You should share code only within your team, and not with other students in the class. You are *not* allowed to copy code from the web.

2.1 Structure and comments

Before starting to write code, you should outline an appropriate code structure and maintain a consistent line of communication with your teammates. There will be a group created for you inside bCourses where you can collaborate with your team members. Make sure to outline the various sections of code you will need to develop to accomplish the project as a whole, as this will help you tackle the project as a team. Needless to say, comments within your code will become essential for conveying its meaning to the other members of your group. Because of this, you will be graded on your overall code structure and comments. These should be easy points, but they are here to encourage you to use strong coding practices that will help you save time in the long run, especially when collaborating with others.

[Optional: Try to structure your code such that the same or similar functions do not appear again unnecessarily. This will require careful thinking on which procedures are best defined in their own sub-functions and what values should be passed from sub-function to sub-function.]

2.2 Details

- Your app should be saved as `climatewedges.mlapp`
- Type `appdesigner` at the Matlab command prompt to launch `appdesigner` within Matlab. Select Open > Interactive Tutorial to learn the basics.
- After you have saved your draft app file, you can open it again by typing `appdesigner climatewedges`.
- Make sure you are using Matlab 2017b. The `appdesigner` is a relatively new feature in Matlab (be patient with it) so please use 2017b (this version is installed on the Etcheverry computers). If you have trouble, close other applications and restart Matlab. (Note: use `appdesigner` and do **NOT** use GUIDE to create your app in Matlab.)
- A text file with details about the 15 wedges is provided on bCourses for you to incorporate into your app. Most wedge strategies may be used more than once, but not

all cuts can come from one energy sector. Detailed constraints are provided through input files, see below. Your app will output a summary file as well.

- There is no right answer. There is no easy or “right” solution to the carbon and climate problem (or to this game). Think of it as an educational and policy-making tool.

2.3 Aesthetics

In the real world, the success of an app depends at least partially on how user-friendly and aesthically-pleasing it is. Your app will be graded on aesthetics and ease of use. Some things to consider:

- Text in text boxes, labels, legends should not be obscured and should be legible.
- App should be clearly laid out and easy to navigate.

Optional aesthetics improvements to consider might include choosing a color theme for the UI figure, keeping text and labels legible even if the figure is manually resided, having fixed axis limits, and optimizing spacing of UI elements even if it is resized.

2.4 Input files

Your app should be able to allow the user to specify the locations of three plaintext (.txt) files, representing: the possible wedges, the constraints, and a strategy. These input files will make it easier to test your code.

2.4.1 Wedges file

A semicolon-separated plaintext file that describes the available 15 wedges is provided for you (`wedges.txt`), which contains all the information in the table on the first page of the Appendix. The file has one header line followed by one line of values per wedge. Each line contains that wedge’s ID, category, sector, cost and other details. The ID is a numerical identifier for the wedge, which will be re-used in the strategy text file. The four sectors are Electricity Production (E), Heating and Direct Fuel Use (H), Transportation (T), and Biostorage. Some wedges have multiple sectors. In that case, the sectors will be listed comma-separated (remember the larger line is semicolon-separated). Cost here is given simply as 1, 2 or 3, with 3 being the most expensive. The Matlab function `strsplit` may be useful here when reading in the data.

Your GUI should be able to take the location of the wedges file as an input and load the file correctly.

2.4.2 Portfolio file, constraints on strategies

This file is a space-separated plaintext file that describes how the total carbon emissions are divided between the sectors. There is a single header line followed by one line per sector. Each line contains the name of the sector, followed by a space, then the number of GtC emissions contributed by that sector.

Within the three carbon producing sectors, we cannot possibly save more carbon then we produce. Therefore there are constraints on the make-up of a given set of strategies. For example, the official game's constraints are that for the 50 year period between 2010 and 2060, selected wedges can include no more than 6 electricity wedges, 5 transportation wedges or 5 heat or direct fuel wedges. This is because the 16 GtC projected to be emitted in 2060 under business as usual are broken up into 6 GtC from the electricity sector, 5 GtC from the transportation sector, and 5 GtC from the heat and direct fuel sector. Because biostorage takes carbon from all sources out of the atmosphere, biostorage wedges do not count toward an energy sector. In this case, the portfolio constraint input file `constraints.txt` would read:

```
Sector Constraints
Electricity 6
Transportation 5
Fuel 5
```

You may be given a portfolio input file with different values. You may assume that the wedges file and the portfolio file will have consistent sector names. That is, the same exact character array will be used to identify sectors in both files. These sector names should not be hardcoded, but should come from the input files so that they can be changed later if needed.

Your GUI should be able to take the location of the constraints file as an input and load the file correctly.

2.4.3 Strategy file

You may also be given a space-separated plaintext file `strategy.txt` that specifies a strategy. There is a single header line followed by one line per wedge to use. Each line contains the ID number of a wedge to be used followed by its starting year (for the base requirements the starting years will all be the same). The ID of each wedge is defined by the wedge input file, and you may leave it to the user to verify that the strategy file uses the correct IDs for the provided wedges file.

The user also has the option of selecting a strategy graphically using the GUI, so a strategy file is an optional input for the user (and will help you when testing your app). Your GUI should be able to take the location of the strategy file as an input and load the file correctly.

2.5 Output file

One feature of your app is that it should be able to print an output file `output.txt` summarizing the wedges selected. This should be a semicolon-separated plaintext file with a header line followed by one line per wedge indicating its ID, name, sector, number of times used, total cost and challenges (taken from the wedges input file).

For example, a strategy that uses only two "Wind Electricity" wedges should read:

```
ID;StrategyName;Sector;NumberUsed;TotalCost;Challenges
10;Wind Electricity;Electricity;2;4;Local opposition
```

3 Project deliverables

3.1 Beta test

Beta testing is an early release of software to friendly users for testing. After spending some time working on the project, you will submit your current version of your code to your GSI for testing and feedback. The only requirements for receiving full credit for the beta test are (1) turning your code in on time, (2) reading in the three text files described above, and (3) having that code return without throwing an error (even if the code is not doing the right thing inside your function). In your submission you can include questions for your GSI so you can get some feedback. Work hard on the project before the beta test, because the more you turn in by this deadline, the more feedback you can get from your GSI.

3.2 Final code - basic requirements

To meet the basic requirements, create an app using Matlab's `appdesigner` that interactively allows the user to select different combinations of wedges and reports on their outcome. The user should be able to graphically provide the app with the locations of three plaintext files that describes the wedges, constraints and strategy to be considered, as outlined in Sec. 2.4. The wedges, constraints and strategy should be loaded into the GUI and the results of the selected combination should be displayed graphically. The user should also be able to manually select different combinations of wedges without providing a strategy file.

Note: meeting these requirements, even if none of the other functionality is met, is your first priority, and will ensure that you earn points from this section. Doing so will also enable you to earn points from further testing.

Here is a checklist of basic requirements for your app:

1. Load the mitigation strategies described in the wedges input file and make them available for selection. The user should have the ability to select multiple wedges one at a time and should be able to clear their strategy and start over.
2. Check that the selected combination of wedges does not violate the constraints described in the portfolio/constraints file (if one is provided) when each new wedge is selected. You may use a strategy more than once, but only use whole numbers of wedges. A single strategy should not account for more than half the wedges used.
3. Have the ability to write a plaintext output file recording the selected strategies, sector, cost, challenges. The location of this output file should be specified by the user in the GUI. See Sec. 2.5 for format.
4. Include a graphical display of the selected wedges in a plot of carbon emissions vs. year (similar to Figure 3).
   - Plot the historical emissions data from 1959 – 2017 (`historicaldata.txt` provided on bCourses).
   - The business as usual emission projections should be plotted for years 2018 to 2068 using Equation 3.
   - The flat line emissions should be plotted as a horizontal line starting from the current year emissions.
   - Shade each wedge with the appropriate color related to the category of the mitigation strategy which the wedge represents based on Fig. 4.
   - Label each wedge so that the corresponding strategy can be identified.
   - Give all axes informative labels; include units when necessary.
   - Your figure should span from years 1959 to 2068.
5. Include a feature in the GUI (in addition to the strategy file) for selecting which year the mitigation strategies begin.
   - Possible start years should range from 2018 to 2068.
   - For the basic requirements all wedges will begin on the same year (but that year is a user input).
6. Display the total number of wedges selected, the number selected from each sector compared to the sector's specified constraint, and the minimum number of wedges required for the carbon emission rate to "flatline" (hint: all wedges have a 1 GtC/yr reduction after 50 years, and a wedge's maximum contribution is when it's implemented immediately).
7. Display the total "cost" of the mitigation strategy by summing the costs associated with each selected wedge (this is one of the fields in the wedges input file).

8. **Your app must not crash if given improperly-formatted input files or incorrect file paths.** No Matlab errors should be thrown regardless of user input to the GUI or in the input files (your app **can** and should display its own errors to the user).

    - To debug, test the range of possible inputs the user may give, *e.g.* try both minimum and maximum values for mitigation start year, test that incorrect input files do not cause Matlab errors, etc.

9. Your program should quickly (within a few seconds) respond to user inputs when asked to perform the required basic functionality. Your program may take longer time to perform additional/advanced functionality, but this should be described in your writeup. In other words, if your program takes longer to compute, your writeup (see below) should explain and justify why. The grading will be done on the computers of the Etcheverry E7 computer lab.

3.3 Final code - intermediate objectives

In addition to your code successfully meeting the basic requirements above, you will earn additional points if you add additional functionality to your code.

The following is a list of intermediate objectives:

1. Allow the user to add/remove individual wedges one at a time.

2. Display the minimum number of wedges required (by 2068) to either 1) flat line the CO_2 emissions at the year the mitigation strategies are first implemented, 2) cut emissions to 1990 levels, or 3) cut emissions to 80% below 1990 levels (e.g. the State of California has a goal to do this for state emissions by 2050). The user should be able to toggle which option is displayed.

3. Plot (a) atmospheric carbon CO_2 concentrations vs. time, and (b) mean warming vs. time (in addition to plotting the emissions).

    - This can be done on separate graphs, on a different tab, or with a toggle that allows the user to select what information is plotted on the same axes.
    - For CO_2 concentrations, refer to Equation 4 and the conversions to ppm above. For the plot of global mean warming, refer to Equation 6 above to plot ΔT as a function of time. At start-up, set the calculation to use a default value of $\lambda = 0.7°\text{C}$ per W/m^2. Because the value of λ is still under debate, add a feature to allow the user to change the value of this parameter.

3.4 Final code - advanced objectives

In addition to your code successfully meeting the basic requirements and intermediate objectives above, you will earn additional points if you add even more functionality to your code. You may implement advanced objectives without having exhausted the intermediate objectives.

The following is a list of possible advanced objectives. Note that you do NOT need to complete all of these. Completing at least 3 of the 5 options below at a satisfactory level will give you full credit on this section.

1. Allow different stabilization wedge strategies to be started at different years (both graphically and from the input file). Explain this feature in your write up.
2. Display brief explanatory text about each selected wedge as the user selects it (see the info in the `wedges.txt` file, or include other useful tips/info for the user).
3. Include an input for target emissions rate and year and report the cheapest mitigation strategy to reach this goal given the current constraints.
4. Propose a new wedge and justify it (including brief numerical calculations of carbon savings and approximation of cost) in your write-up.
5. Add an advanced new feature of your choice! Be creative! Explain this in your write-up.

Here are some (optional!) questions to consider as you design your app and create your writeup. These are to inspire you to think deeper about the stabilization wedges framework and perhaps come up with ideas on how to incorporate these questions into the user interface in some form.

- Given physical challenges and risks, how many wedges do you think each wedge strategy can each realistically provide?
- In choosing wedge strategies, it's important to avoid double counting - removing the same emissions with two different strategies. For example, there are 6 strategies for cutting emissions from electricity, but we project only 5 wedges worth of carbon produced from the electric sector 50 years from now. Can you think of reasons, other than the adoption of alternative or nuclear energy, that emissions from electricity would be lower or higher than we predict? Examples: increased use of carbon-intensive coal versus natural gas (higher), slower population growth (lower), substitution of electricity for fuel, as via plug-in electric cars (higher).
- Industrialized countries and developing countries now each contribute about half the world's emissions, although the poorer countries have about 85% of the world's population. (The U.S. alone emits one fourth of the world's CO_2.) If we agree to freeze

global emissions at current levels, that means if emissions in one region of the world go up as a result of economic/industrial development, then emissions must be cut elsewhere. Should the richer countries reduce their emissions 50 years from now so that extra carbon emissions can be available to developing countries? If so, by how much?

- Nuclear energy is already providing one-half wedge of emissions savings - what do you think the future of these plants should be?
- Automobile emissions are a popular target for greenhouse gas cuts. What percent of greenhouse gases do you think come from the world's passenger vehicles? (answer: about 18%)

3.5 Final writeup

Your final project submission will include a 2 page executive summary describing your app. This will include a 1-page overview of your algorithm and how it works and the design decisions you made, including listing your selected advanced features (if any). Also include a 1-page example showing output from using your app with descriptive text and explanations, i.e. discuss the stabilization wedges chosen, justification, costs, etc. Think of this like a marketing advertisement for your code, highlighting the key features and making it easy for your customer (potential users of the app) to understand what you did. Include a title and your team member names at the top of your summary, and make proper use of headings, sections, figures, as needed to support the text.

Your writeup will be graded by your GSIs based on the use of appropriate technical writing and the adequacy of your description (we should be able to to understand your methodology without looking at your code). Also make sure you are within the page limit to receive full credit.

3.6 Grading breakdown

You will be scored out of 100 points as a group as follows:

- Beta test - 15 points
- Final code - 70 points
  - Structure and comments - 5 points
  - Aesthetics - 5 points
  - Basic requirements - 30 points
  - Intermediate objectives - 15 points
  - Advanced objectives - 15 points

- Final writeup - 15 points

All team members will pull an equal weight, contributing where each person has greatest strengths and combining your skills to accomplish more. If there are problems with your group, please let your GSI know AS SOON AS POSSIBLE.

The grading of your function will be done on the computers of the Etcheverry E7 computer lab. You should **not** use functions or other Matlab functionality that are **not** already installed on the computers of the Etcheverry E7 computer lab.

4 Tips and tricks - things to keep in mind

- Start with this tutorial on how to use App Designer: `https://www.mathworks.com/help/matlab/creating_guis/create-a-simple-app-or-gui-using-app-designer.html#bvk_lfd-1`
- Be creative! This is an open-ended project, so there is no right or wrong way to code the solution.
- Brainstorm! Spend time with your team talking about different approaches you could take. Think about all the concepts you have learned in class and how you might apply each of them to your project, e.g. iteration, recursion, branching, regression, root finding, series, interpolation, integration, Monte Carlo approaches, etc. You never know what might trigger a new idea.
- Be inspired by the real Stabilization Wedges game and think about which elements of the human decision making process that you can enhance with your app.
- Always put basic functionality first, ahead of fancy features (for example, make sure your function meets the basic and intermediate requirements described above before worrying about extra features).
- Create a modular program so you can divide the project into pieces that can be tested individually and that each team member can work on. Test the pieces separately before putting them all together. This will help with debugging!
- Your code should be well commented. This will facilitate collaboration among all team members.
- We encourage you to make up your own test cases to test how your app performs in a variety of situations.
- Beautiful apps with the best functionality may be posted online (with your permission) to become an educational and policy-making resource!! Who knows, you could get famous and end up making a major contribution to climate change mitigation and education!

- Realize that your code may not be as good as a human at making some decisions. There may be some aspects where your code fails and a human would have to intervene to fix it. Even creating a tool to mimic the manual process will be a benefit, so the goal is to do your best! Strategize about how to design your code to meet the basic and intermediate requirements first, then go as far as you can go with it!

- Yes, this is an open-ended project and it is hard. But everything feels impossible until it actually becomes possible. Rest assured that we know this is hard and will be reasonable with the grading. Follow the guidelines above, and don't forget to have fun with this!!

5 References and extra information

- Climate Stabilization Wedges website: http://cmi.princeton.edu/wedges/
- Pacala, S. and R. Socolow. 2004. Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science* **305**(5686), 968-972.
- Socolow, R. and S.H. Lam. 2007. Good enough tools for global warming policy making. *Phil. Trans. R. Soc. A*, **365**, 897-934.
- Williams, J.H. et al. 2012. Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity, *Science* **335**, 53-59.
- Wedges Reaffirmed: http://www.climatecentral.org/blogs/wedges-reaffirmed/P1
- Davis, S.J. et al. 2013. Rethinking wedges, *Environmental Research Letters* **8**, 011001.
- Johan Rockström TED talk: Let the environment guide our development
- Per Espen Stoknes TED talk: How to transform apocalypse fatigue into action on global warming
- Global Carbon Budget: http://www.globalcarbonproject.org/carbonbudget/index.htm
- U.S. Stabilization Wedges, Scientific American article: https://www.scientificamerican.com/article/us-stabilization-wedges/
- Wedges calculations and details: http://cmi.princeton.edu/wedges/pdfs/science_support.pdf
- Wedges song! https://www.youtube.com/watch?v=-wcDHZ7Z-hQ

6 Submission instructions and important dates

Note that minor updates to the project guidelines may be posted at a later date - it is your responsibility to follow up and read announcements related to the project.

6.1 Beta test - due April 9 at 12pm on bCourses

This is an easy way to earn points for the project; see above for details. Also remember that this is a great opportunity to get feedback if you are stuck on the problem. Your project group will have a single submission in bCourses. You must submit your app file called `climatewedges.mlapp`.

6.2 Final submission - due April 27 at 12pm on bCourses

Make sure to get it uploaded early, well before the deadline! Your project group will have a single submission in bCourses. You must submit **two** files:

- Your write-up **in pdf format**, titled `wedges.pdf`
- The `climatewedges.mlapp` file that contains your app.

6.3 Project showcase - Monday April 30, 2-3 pm (during lecture)

We will celebrate what we have learned during the project in addition to doing a review for the final exam, both during lecture.

Best of luck to you all! Remember to have fun with this!
GO BEARS!

Appendix

Stabilization Wedges – 15 Ways to Cut Carbon

= Electricity Production, =Heating and Direct Fuel Use, =Transportation, = Biostorage

Strategy	Sector	Description	1 wedge could come from…	Cost	Challenges
1. Efficiency – Transport		Increase automobile fuel efficiency (2 billion cars projected in 2050)	**… doubling the efficiency of all world's cars from 30 to 60 mpg**	**$**	Car size & power
2. Conservation - Transport		Reduce miles traveled by passenger and/or freight vehicles	**… cutting miles traveled by all passenger vehicles in half**	**$**	Increased public transport, urban design
3. Efficiency - Buildings		Increase insulation, furnace and lighting efficiency	**… using best available technology in all new and existing buildings**	**$**	House size, consumer demand for appliances
4. Efficiency – Electricity		Increase efficiency of power generation	**… raising plant efficiency from 40% to 60%**	**$**	Increased plant costs
5. CCS Electricity		90% of CO_2 from fossil fuel power plants captured, then stored underground (800 large coal plants or 1600 natural gas plants)	**… injecting a volume of CO_2 every year equal to the volume of oil extracted**	**$$**	Possibility of CO_2 leakage
6. CCS Hydrogen		Hydrogen fuel from fossil sources with CCS displaces hydrocarbon fuels	**… producing hydrogen at 10 times the current rate**	**$$$**	New infrastructure needed, hydrogen safety issues
7. CCS Synfuels		Capture and store CO_2 emitted during synfuels production from coal	**… using CCS at 180 large synfuels plants**	**$$**	Emissions still only break even with gasoline
8. Fuel Switching – Electricity		Replacing coal-burning electric plants with natural gas plants (1400 1 GW coal plants)	**… using an amount of natural gas equal to that used for all purposes today**	**$**	Natural gas availability
9. Nuclear Electricity		Displace coal-burning electric plants with nuclear plants (Add double current capacity)	**… ~3 times the effort France put into expanding nuclear power in the 1980's, sustained for 50 years**	**$$**	Weapons proliferation, nuclear waste, local opposition
10. Wind Electricity		Wind displaces coal-based electricity (10 x current capacity)	**… using area equal to ~3% of U.S. land area for wind farms**	**$$**	Not In My Back Yard (NIMBY)
11. Solar Electricity		Solar PV displaces coal-based electricity (100 x current capacity)	**.. using the equivalent of a 100 x 200 km PV array**	**$$$**	PV cell materials
12. Wind Hydrogen		Produce hydrogen with wind electricity	**… powering half the world's cars predicted for 2050 with hydrogen**	**$$$**	NIMBY, Hydrogen infrastructure, safety
13. Biofuels		Biomass fuels from plantations replace petroleum fuels	**… scaling up world ethanol production by a factor of 12**	**$$**	Biodiversity, competing land use
14. Forest Storage		Carbon stored in new forests	**… halting deforestation in 50 years**	**$**	Biodiversity, competing land use
15. Soil Storage		Farming techniques increase carbon retention or storage in soils	**… practicing carbon management on all the world's agricultural soils**	**$**	Reversed if land is deep-plowed later

For more information, visit our website at http://cmi.princeton.edu/wedges.

Increased Efficiency & Conservation

1. Transport Efficiency

A typical 30 miles per gallon (30 mpg) car driving 10,000 miles per year emits a ton of carbon into the air annually. Today there are about about 600 million cars in the world, and it's predicted that there will be about 2 billion passenger vehicles on the road in 50 years. **A wedge of emissions savings would be achieved if the fuel efficiency of all the cars projected for 2060 were doubled from 30 mpg to 60 mpg**. Efficiency improvements could come from using hybrid and diesel engine technologies, as well as making vehicles out of strong but lighter materials.

Cutting carbon emissions from trucks and planes by making these engines more efficient can also help with this wedge. Aviation is the fastest growing component of transportation.

2. Transport Conservation

A wedge would be achieved if the number of miles traveled by the world's cars were cut in half. Such a reduction in driving could be achieved if urban planning leads to more use of mass transit and if electronic communication becomes a good substitute for face-to-face meetings.

3. Building Efficiency

Today carbon emissions arise about equally from providing electricity, transportation, and heat for industry and buildings. The largest potential savings in the buildings sector are in space heating and cooling, water heating, lighting, and electric appliances.

It's been projected that the buildings sector as a whole has the technological and economic potential to cut emissions in half. **Cutting emissions by 25% in all new and existing residential and commercial buildings would achieve a wedge worth of emissions reduction.** Carbon savings from space and water heating will come from both end-use efficiency strategies, like wall and roof insulation, and renewable energy strategies, like solar water heating and passive solar design.

4. Efficiency in Electricity Production

Today's coal-burning power plants produce about one-fourth of the world's carbon emissions, so increases in efficiency at these plants offer an important opportunity to reduce emissions**. Producing the world's current coal-based electricity with doubled efficiency would save a wedge worth of carbon emissions.**

More efficient conversion results at the plant level from better turbines, from using high-temperature fuel cells, and from combining fuel cells and turbines. At the system level, more efficient conversion results from more even distribution of electricity demand, from cogeneration (the co-production of electricity and useful heat), and from polygeneration (the co-production of chemicals and electricity).

Due to large contributions by hydropower and nuclear energy, the electricity sector already gets about 35% of its energy from non-carbon sources. Wedges can only come from the remaining 65%.

Suggested Link:
IPCC Working Group III Report "Mitigation of Climate Change", Chapters 4, 5 & 6
http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg3_report_mitigation_of_climate_change.htm

Carbon Capture & Storage (CCS)

If the CO_2 emissions from fossil fuels can be captured and stored, rather than vented to the atmosphere, then the world could continue to use coal, oil, and natural gas to meet energy demands without harmful climate consequences. The most economical way to pursue this is to capture CO_2 at large electricity or fuels plants, then store it underground. This strategy, called carbon capture and storage, or **CCS**, is already being tested in pilot projects around the world.

5. CCS Electricity

Today's coal-burning power plants produce about one fourth of the world's carbon emissions and are large point-sources of CO_2 to the atmosphere. **A wedge would be achieved by applying CCS to 800 large (1 billion watt) baseload coal power plants or 1600 large baseload natural gas power plants in 50 years. As with all CCS strategies, to provide low-carbon energy the captured CO_2 would need to be stored for centuries.**

There are currently 3 pilot storage projects in the world, which each store about 1 million tons of carbon underground per year. Storing a wedge worth of emissions will require 3500 times the capacity of one of these projects.

6. CCS Hydrogen

Hydrogen is a desirable fuel for a low-carbon society because when it's burned the only emission product is water vapor. Because fossil fuels are composed mainly of carbon and hydrogen they are potential sources of hydrogen, but to have a climate benefit the excess carbon must be captured and stored.

Pure hydrogen is now produced mainly in two industries: ammonia fertilizer production and petroleum refining. Today these hydrogen production plants generate about 100 million tons of capturable carbon. Now this CO_2 is vented, but only small changes would be needed to implement carbon capture. **The scale of hydrogen production today is only ten times smaller than the scale of a wedge of carbon capture.**

Distributing CCS hydrogen, however, requires building infrastructure to connect large hydrogen-producing plants with smaller-scale users.

7. CCS Synfuels

In 50 years a significant fraction of the fuels used in vehicles and buildings may not come from conventional oil, but from coal. When coal is heated and combined with steam and air or oxygen, carbon monoxide and hydrogen are released and can be processed to make a liquid fuel called a "synfuel."

Coal-based synfuels result in nearly twice the carbon emissions of petroleum-derived fuels, since large amounts of excess carbon are released during the conversion of coal into liquid fuel. The world's largest synfuels facility, located in South Africa, is the largest point source of atmospheric CO_2 emissions in the world. **A wedge is an activity that, over 50 years, can capture the CO_2 emissions from 180 such coal-to-synfuels facilities.**

Suggested link:
IPCC Special Report on Carbon dioxide Capture and Storage, SPM
http://www.ipcc.ch/pdf/specialreports/srccs/srccs_summaryforpolicymakers.pdf

Fuel Switching

8. Fuel-Switching for Electricity

Because of the lower carbon content of natural gas and higher efficiencies of natural gas plants, producing electricity with natural gas results in only about half the emissions of coal. **A wedge would require 1400 large (1 billion watt) natural gas plants displacing similar coal-electric plants.**

This wedge would require generating approximately four times the Year 2000 global production of electricity from natural gas. In 2060, 1 billion tons of carbon per year would be emitted from natural gas power plants instead of 2 billion tons per year from coal-based power plants.

Materials flows equivalent to one billion tons of carbon per year are huge: a wedge of flowing natural gas is equivalent to 50 large liquefied natural gas (LNG) tankers docking and discharging every day. Current LNG shipments world-wide are about one-tenth as large.

Suggested link:
U.S. Environmental Protection Agency: Electricity from Natural Gas
http://www.epa.gov/RDEE/energy-and-you/affect/natural-gas.html

Nuclear Energy

9. Nuclear Electricity

Nuclear fission currently provides about 17% of the world's electricity, and produces no CO_2. **Adding new nuclear electric plants to triple the world's current nuclear capacity would cut emissions by one wedge if coal plants were displaced.**

In the 1960s, when nuclear power's promise as a substitute for coal was most highly regarded, a global installed nuclear capacity of about 2000 billion watts was projected for the year 2000. The world now has about one-sixth of that envisioned capacity. If the remainder were to be built over the next 50 years to displace coal-based electricity, roughly two wedges could be achieved.

In contrast, phasing out the worlds' current capacity of nuclear power would require adding an additional half wedge of emissions cuts to keep emissions at today's levels.

Nuclear fission power generates plutonium, a fuel for nuclear weapons. These new reactors would add several thousand tons of plutonium to the world's current stock of reactor plutonium (roughly 1000 tons).

IPCC Working Group III Report "Mitigation of Climate Change", Chapter 4 - Energy Supply
http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-chapter4.pdf

10. Wind Electricity

Wind currently produces less than 1% of total global electricity, but wind electricity is growing at a rate of about 30% per year. **To gain a wedge of emissions savings from wind displacing coal-based electricity, current wind capacity would need to be scaled up by a factor of 10.**

This increase in capacity would require deployment of about 1 million large windmills. Based on current turbine spacing on wind farms, a wedge of wind power would require a combined area roughly the size of Germany. However, land from which wind is harvested can be used for many other purposes, notably for crops or pasture.

11. Solar Electricity

Photovoltaic (PV) cells convert sunlight to electricity, providing a source of CO_2-free and renewable energy. The land demand for solar is less than with other renewables, but **installing a wedge worth of PV would still require arrays with an area of two million hectares, or 20,000 km^2.** The arrays could be located on either dedicated land or on multiple-use surfaces such as the roofs and walls of buildings. The combined area of the arrays would cover an area the size of the U.S. state of New Jersey, or about 12 times the size of the London metropolitan area.

Since PV currently provides less than a tenth of one percent of global electricity, achieving a wedge of emissions reduction would require increasing the deployment of PV by a factor of 100 in 50 years, or installing PV at about 2.5 times the 2009 rate for 50 years.

A current drawback for PV electricity is its price, which is declining but is still 2-5 times higher than fossil-fuel-based electricity. Also, PV can not be collected at night and, like wind, is an intermittent energy source.

12. Wind Hydrogen

Hydrogen is a desirable fuel for a low-carbon society because when it's burned the only emission product is water vapor. To produce hydrogen with wind energy, electricity generated by wind turbines is used in electrolysis, a process that liberates hydrogen from water. **Wind hydrogen displacing vehicle fuel is only about half as efficient at reducing carbon emissions as wind electricity displacing coal electricity, and 2 million (rather than 1 million) windmills would be needed for one wedge of emissions reduction.** That increase would require scaling up current wind capacity by about 20 times, requiring a land area roughly the size of France.

Unlike hydrogen produced from fossil fuels with CCS, wind hydrogen could be produced at small scales where it is needed. Wind hydrogen thus would require less investment in infrastructure for fuel distribution to homes and vehicles.

Renewables & Biostorage (cont'd)

13. Biofuels

Because plants take up carbon dioxide from the atmosphere, combustion of biofuels made from plants like corn and sugar cane simply returns "borrowed" carbon to the atmosphere. Thus burning biofuels for transportation and heating will not raise the atmosphere's net CO_2 concentration.

The land constraints for biofuels, however, are more severe than for wind and solar electricity. Using current practices, just one wedge worth of carbon-neutral biofuels would require 1/6th of the world's cropland and an area roughly the size of India. Bioengineering to increase the efficiency of plant photosynthesis and use of crop residues could reduce that land demand, but large-scale production of plant-based biofuels will always be a land-intensive proposition.

Ethanol programs in the U.S. and Brazil currently produce about 20 billion gallons of biofuel per year from corn and sugarcane. **One wedge of biofuels savings would require increasing today's global ethanol production by about 12 times, and making it sustainable.**

14. Forest Storage

Land plants and soils contain large amounts of carbon. Today, there is a net *removal* of carbon from the atmosphere by these "natural sinks," in spite of deliberate deforestation by people that *adds* between 1 and 2 billion tons of carbon to the atmosphere. Evidently, the carbon in forests is increasing elsewhere on the planet.

Land plant biomass can be increased by both reducing deforestation and planting new forests. **Halting global deforestation in 50 years would provide one wedge of emissions savings.** To achieve a wedge through forest planting alone, new forests would have to be established over an area the size of the contiguous United States.

15. Soil Storage

Conversion of natural vegetation to cropland reduces soil carbon content by one-half to one-third. However, soil carbon loss can be reversed by agricultural practices that build up the carbon in soils, such as reducing the period of bare fallow, planting cover crops, and reducing aeration of the soil (such as by no till, ridge till, or chisel plow planting). **A wedge of emissions savings could be achieved by applying carbon management strategies to all of the world's existing agricultural soils.**

Suggested links:
U.S. DOE, Energy Efficiency & Renewable Energy
http://www.eere.energy.gov/

IPCC Working Group III Report "Mitigation of Climate Change", Chapters 8 & 9
http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg3_report_mitigation_of_climate_change.htm