Analyzing and visualizing the synergistic impact mechanisms of climate change related costs

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April 2014

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Abstract
One climate related phenomenon could affect many more. The direct costs associated to climate related factors pass to a number of other climate related costs through the indirect economic consequences of climate change. In this paper we propose a mathematical model which aims to provide forecasts of the distribution of the costs caused by the synergistic mechanism of environmental effects. The model is created to be directly applied to situations where the primary costs associated to climate related factors can be specified. It is expressed in matrix terms and is programmed using *Mathematica*'s matrix functions. We provide the framework for efficient computation of this model, covering possible linear and nonlinear functions of the impact mechanism for costs and, infinite direct cost scenarios. Some directions for the quantitative estimation of impact indicators and adaptation potentials of the costs incurred by certain climate related factors are included, in order to apply the proposed model using real socioeconomic data.

Keywords: Computational techniques; *Mathematica* computer software; Climate change related factors; Cost interactions.

JEL Codes: Q54; Q50; Q58; C63; C88.

Acknowledgments
An earlier version of this paper was presented in the 1st PanHellenic Conference in "Natural Resource and Environmental Economics: Climate Change" at Volos 26-27 March 2014. Thanks are due to the participants in the Conference for helpful comments and discussions.

1. Introduction

Societies depend entirely on ecosystems and the associated offered services like, among others, water and food provisions, operating in global biogeochemical cycling, raw materials and regulation of the climate (Dixon 1986; Barbier 1994; MEA 2005). The global climate change is a very complex issue and it is even more difficult to tackle and cope with due to its long-run character and the various synergistic effects stemming from its impacts.

The synergistic impact mechanism of environmental effects produces the «colliding steel spheres effect», meaning that one climate related phenomenon could affect many more. In many environmental studies it is claimed that parallel interactions among climate effects is a possible situation (IPCC, 2001; 2007; 2012 a,b; Fűr and Csete, 2010; Mantyka-Pringle et al., 2012; European Commission SWD, 2013). In the report published by IPCC (2001) climate change impacts are presented and analyzed on a matrix of potential for interactions and synergistic effects.

In the present study we generate visual schemes of the direct synergistic effects between climate related factors in several human settlement and industry types. Considering the primary costs caused by climate related factors, we assume that the synergistic impact mechanism among certain climate related factors allows for a similar synergistic impact mechanism of the corresponding primary costs.[1] With notations and operations of matrix algebra, using either a technical coefficient or a functional matrix to illustrate climate related cost interactions and synergistic effects, we formulate a local scale model that forecasts the cost distribution which the direct synergistic mechanism causes from the direct costs of certain climate related factors.

We create the computational framework to apply the proposed model in a qualitative and a quantitative approach. For this purpose a main computer algebra system, *Mathematica*[2]

[1] Primary costs may be identified as direct costs while secondary costs may be considered as synergistic.
[2] *Mathematica* software is tradable from Wolfram Research, Inc.

is used to generate our model's output, both visually and numerically. Specifically, in *Mathematica*'s computational environment, we create pattern constructs consisting of colored patches which describe the synergistic impact mechanism of climate related factors.

In this way, we provide initially a concise framework for synthesizing and displaying the data on an area's human-economic system. Then our predictive model is applied by using hypothetical data and *Mathematica*'s dynamic visualization options, in order to generate versions of cost distribution snapshots, with controls added to allow interactive manipulation for the value of impact indicators of cost interactions, the synthesis of the direct cost distribution and the amount of costs. Our model and its computational aspects allow for clear visual comparisons among certain settlement and industry types. The proposed model is well suited to perform sensitivity analyses in cases of settlements and industries and also to evaluate climate policies.

Finally, our contribution provides directions for quantitative estimates of impacts and adaptation potentials of the costs incurred by climate change related factors. It also ensures the model's applicability guiding for future applications on the economic costs of certain ecosystem inputs like migration, flooding-landslides-fires, air and water pollution, human health and energy by the use of available appropriate socioeconomic data.

The structure of the paper is the following. The next section discusses the visualization of the interactions first in the case of different settlement types and next to industry types. Section 3 proposes a linear and nonlinear cost analysis with different climate change scenarios and derives indicative estimates of the potential costs. Section 4 provides some insights in terms of performing an empirical application of the proposed model formulation while the last section concludes the paper.

2. Visualizing the interactions among climate related factors

2.1 The case of settlement types

Humans depend on the ecosystems and they are part of the ecosystems they live on (Wilson 2002; Puglise & Kelty 2007). Obviously a healthy ecosystem has the ability to sustain healthy human populations (Rapport et al. 1998). Most of the population in Earth lives in settlements in a way that their concentrations may result to vulnerabilities to local specific events. Vulnerability refers to the way a system reacts to the degradation imposed from its exposure to various risks.[3]

Human settlements and coastal zones are influenced significantly by coastal and riverine flooding, fires, etc. The risks and uncertainties of the consequences of global warming are of interest. The sea level rise will influence coastal areas and the use of land and may threaten the survival of some coastal communities. Extreme weather conditions and patterns leading to heat waves, floods and droughts change the climate condition of some areas with resulting consequences like storms appearing more often and more intensively.

The higher weather variability and the more extreme events may also affect the energy sector by increased demand for air-conditioning and reduced demand for space heating. This may be accompanied by the concern of electricity producers related to the reliability of their systems to cope with these changeable weather conditions (Kolstad and Toman, 2005). Similarly, water infrastructure will be at risk with changes in precipitation to question the ability of the current infrastructure of dams and reservoirs (Kolstad and Toman, 2005).

If extreme weather conditions remain then some local areas will face problems to sustain the existing population resulting to migration and dislocation. The effects are serious and may range from loss of land and coastal flooding from the sea level rise, health problems with more deaths and tropical diseases, increased storms and floods to migration. Flooding

[3] Vulnerability to effects of climate change may be defined as the degree a system, subsystem or system component experiences harm from its exposure to a perturbation or source of stress (Clark et. 2000; Turner et al. 2003; IPCC, 2007).

may be considered as one of the most serious effects of climate change on human settlements with riverine and coastal settlements to be at high risk (IPCC, 2001).

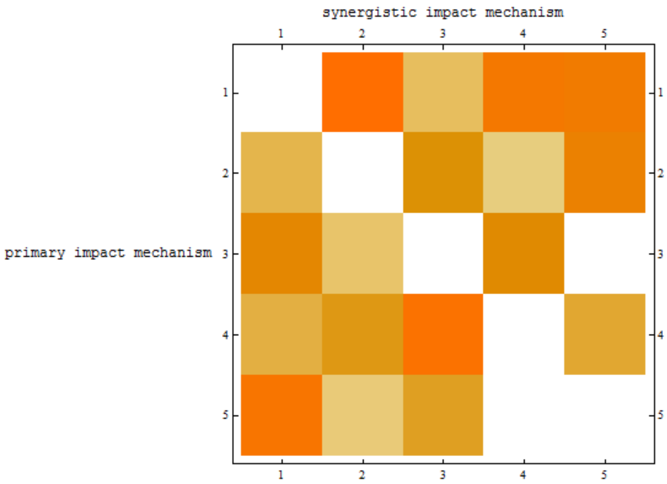
IPCC (2001) presents a matrix of synergistic effects between climate associated factors influencing human settlements and industry types.[4] In our proposed computational approach and in the case of urban settlements, the interactions between migration, phenomena of flooding-landslides-fires, air and water pollution, human health and access to energy – clean water and other resources necessary to sustain human settlements and their populations are featured in a 5×5 matrix (Figure 1). Each cell identifies a synergistic effect between the climate impact featured in the row and another effect shown in the column.

The pattern constructs of synergistic effects is created in *Mathematica*, for three types of settlements; namely, urban settlements, riverine-coastal-steeplands and resource dependent settlements, as defined in IPCC (2001, par. 7.6.2). According to IPCC (2001) *urban settlements* may suffer from flooding, storm drains and sewers or from accommodating, migrant populations and suffering from urban heat island with significantly warmer conditions compared to its surroundings with consequences to health and energy demand. Similarly, *riverine and coastal settlements* may be affected mostly by flooding from the rise of the sea level while steeplands may become more vulnerable than landslides. Finally, *resource dependent settlements* depend on the availability of natural resources in an area (region) and on the extent that they are vulnerable to climate changes. Examples may be considered hunting and artisanal fishing communities (IPCC, 2001).

In the screenshots produced, white cells make the junction of two unrelated factors. Each colored cell illustrates an interaction between two environmental effects. In our computational approach, infinite matrices of synergistic effects can be constructed, but the tendencies or patterns of interactions observed in the systems are preserved.

[4] For a detailed analysis of human settlements and the associated impacts of climate change see IPCC (2001, chapter 7).

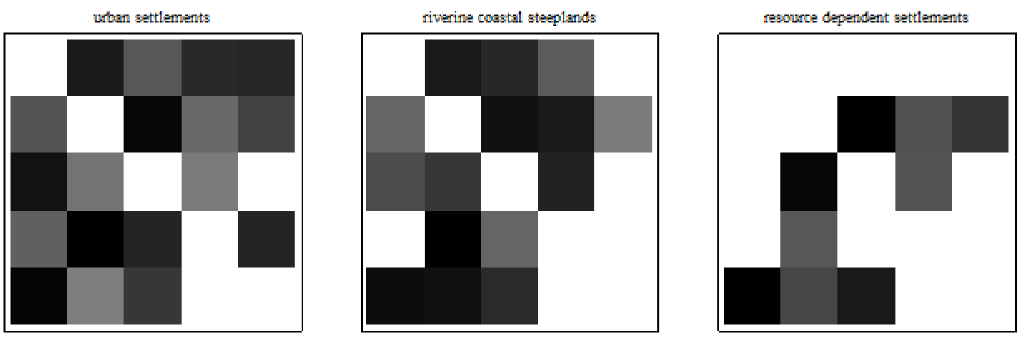
Figure 1: Matrix of synergistic effects for urban settlements.
Serial numbers 1-5 correspond to the following factors:
1. Migration, 2. Flooding, Landslides, Fire, 3. Air and Water Pollution, 4. Human Health 5. Energy, Water, other Resources



In Figures 2 and 3, in a different visual output in *Mathematica* matrix, cells with different shades of gray state the degree of impact of the synergistic effects. A darker shade is related to a more intensive impact. In the pattern constructs below, white cells are steadily white, while all the other cells vary their shades regionally, depending on the geographic, seasonal and/or sectoral scale. Rows and columns of matrices in Figure 2 feature the same environmental effects as in Figure 1, with the same serial number from 1 to 5.

The matrix patterns produced are indicative of every type of settlement. The sparsest matrix corresponds to resource dependent settlements. This dependence is more possible to intercept the progression of the mechanism to manage environmental effects.

Figure 2: Matrix of synergistic effects for settlements:
Urban settlements, riverine coastal steeplands and resource dependent settlements

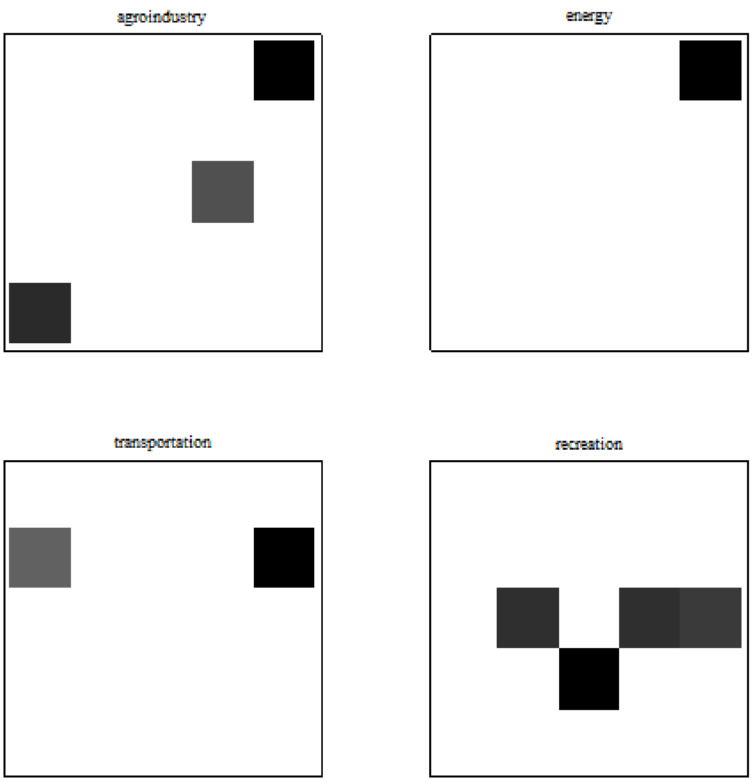


2.2 The case of four industry types

Following IPCC (2001) four industries are considered as reference:

- *Agroindustry* as one of the most adaptable industry affected by climate change with ability to adaptation varying among areas (regions) and groups of farmers within areas (regions);
- *Energy supply and demand* will be influenced with hydropower generation being the most affected and solar energy to depend on cloudiness.
- *Transportation* may be affected by floods, drier climate conditions resulting to heavy rains, by warmer climates softening the asphalt roads and by adverse weather conditions leading to flight cancellations.
- *Recreation and tourism* as a growing industry in many countries which may be affected significantly and in different ways by changes in climate precipitation depending on whether we refer to summer or winter oriented destinations.

Figure 3: Matrix of synergistic effects for industries:
Agroindustry, energy, transportation and recreation



In the pattern constructs for industry types, a white cell indicates no interaction while grey-shaded cells indicate interactions of variant influences. Rows and columns of matrices in Figure 3 feature the same environmental effects as in Figures 1 and 2 with the same serial numbers from 1 to 5.

3. Cost Analysis with Climate Change scenarios

Our model for the types of settlements uses economic or social costs as systems' metrics. An analogous study for the types of industries could constitute a Cost-Benefit Analysis (CBA). In some cases the synergistic effects could act in a beneficial way.

In the proposed predictive model we attempt to forecast the redistribution of the direct costs associated to the five climate related factors mentioned in section 2, using matrix formulations (analogous models in Environmental Economics have been proposed by Martinez de Anguita and Wagner 2010; Stenberg and Siriwardana 2009). Next, the new cost distribution synthesis is defined and its entries are computed considering several direct cost scenarios.

3.1 Linear Interactions of climate related costs

The entries of the matrix of synergistic cost effects are indicators appropriate to evaluate cost interactions. Each indicator defines the measure of the impact between different costs. The matrix entries form the patterns presented in Figure 2, depending on the type of settlement. When linear interactions among costs of environmental effects could constitute a realistic case, multiple regression coefficients[5] could be efficient estimators of impact indicators. Indicators' exact values vary regionally, depending on the geographic, seasonal and/or sectoral scale. Indicators are of dynamic nature and are specific to the settlement and industry type.

[5] These are estimates of the population parameters in a regression analysis. For each explanatory variable there is an estimated coefficient and these coefficients are used to estimate the fitted value of the dependent variable. In the case of multiple regressions, the estimated coefficients indicate the change in the mean response per unit change in the one of the independent variables holding all other independent variables constant (Halkos, 2011).

Given the primary costs associated to one or more climate related effects, we propose a model to evaluate the costs that are generated by the synergistic impact mechanism. Our model is formulated in the matrix algebra context as follows:

$$\begin{pmatrix} c_1 & c_2 & c_3 & c_4 & c_5 \end{pmatrix} \cdot \begin{pmatrix} x_{11} & x_{12} & x_{13} & x_{14} & x_{15} \\ x_{21} & x_{22} & x_{23} & x_{24} & x_{25} \\ x_{31} & x_{32} & x_{33} & x_{34} & x_{35} \\ x_{41} & x_{42} & x_{43} & x_{44} & x_{45} \\ x_{51} & x_{52} & x_{53} & x_{54} & x_{55} \end{pmatrix}, x_{ij} \in \mathrm{R} \qquad (1)$$

where the row matrix $\begin{pmatrix} c_1 & c_2 & c_3 & c_4 & c_5 \end{pmatrix}$ consists of the direct costs associated to the five climate related factors 1-5 mentioned in section 2. $[x_{ij}]$ matrix is the matrix that captures all the repercussions between the five factors and consists of the indicators of impact. The 1×5 row matrix produced, presents the cost distribution created by the synergistic impact mechanism.

3.1.1 Cost scenarios for the types of settlements: changing distributions and costs

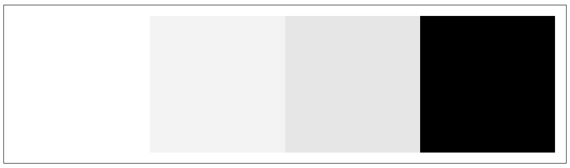
In the hypothetical case studies that follow, we use sample data from *Mathematica*'s random number generator to create matrices with indicators of impact for each one of the three types of settlements: urban, riverine-coastal-steeplands and resource dependent. In all hypothetical case studies examined, we assume negative impacts on economic growth (positive regression coefficients), although impacts on some areas are likely to be positive.[6]

In model (1), the direct cost distribution of climate related factors is defined in the row matrix $\begin{pmatrix} c_1 & c_2 & c_3 & c_4 & c_5 \end{pmatrix}$. In *Mathematica*'s computing environment, the product of the matrix of direct costs with the matrix of synergistic cost effects is depicted in a discrete array of squares. Thus, we have a visual representation of the structure of the re-distribution of

[6] As global warming is mainly a long-run problem its implications are difficult if not impossible to be quantified. Human systems can adapt to climate changes in the long-run. If an area is flooded after climate change occurs migration may take place together with some form of relocation according to the new conditions which after many decades or centuries may lead to full adaptation. Thus the quantification of the consequences of this flooding is ambitious and the costs enormous. For an example see Kolstad and Toman (2005, p. 1566).

costs of the five climate-related factors numbered from 1 to 5 (Figures 5-9). White squares indicate the absence of cost while grey-shaded squares indicate costs with nonnegative values. For example, the row matrix (0, 500, 1000, 10000) is depicted by ArrayPlot function in *Mathematica* as shown in Figure 4.

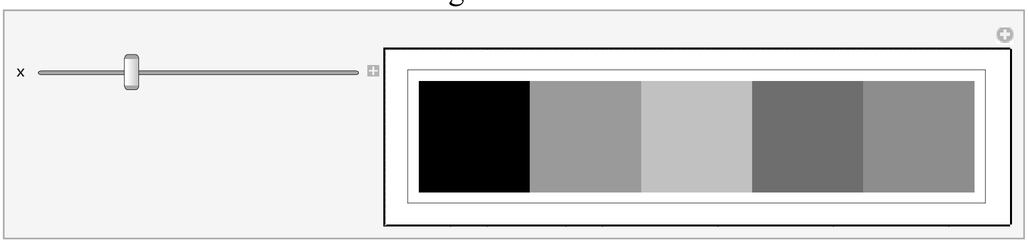
Figure 4: Visualization of row matrix (0, 500, 1000, 10000) using grey-shaded squares



Using *Mathematica*'s dynamic visualization options, we also generate the synthesis of the cost distribution that model (1) predicts, assuming an infinite number of impact indicator values: variable x parameterizes the argument in the random number generator function, making the impact indicator varying (indicatively) from 0.01 to 100 with step 1.

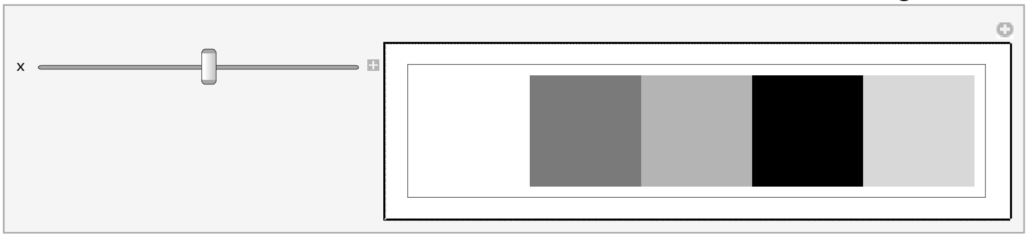
In the first hypothetical case study, we assume direct costs incurring due to factor 2 (flooding-landslides-fires) and 3 (air and water pollution) (the row matrix (0,500,1000,0,0,0) could feature such a case). In urban settlements, these two costs pass to all the other factor costs (Figure 5), while in resource dependent settlements, the final distribution of costs does not include factor 1 (migration) cost (Figure 6). By varying the values of x, we achieve the application of model (1) for infinite matrices of synergistic effects. In all cases we end up with the same matrix structure.

Figure 5: In urban settlements, the synergistic mechanism from c_2 and c_3 costs causes all categories of costs



In another hypothetical case study, we assume a situation where a cost associated to factor 5 (energy, water, other resources) incurs in riverine coastal steeplands. Our model predicts that, after the action of the synergistic impact mechanism, the final cost distribution includes costs for factors 1, 2 and 3. All the other costs are extinguished. The position of the structural matrix elements is guaranteed, when varying index x in the interval of its possible values we continue to have the same visual scheme.

Figure 6: In resource dependent settlements, the synergistic mechanism from c_2 and c_3 costs causes a cost distribution with no cost in migration



In the next computer output, we can examine any possible cost scenario that assumes individual or simultaneous costs associated to certain climate change related factors, in riverine coastal steeplands. Each sliding bar controls the value of each c_i and thus, allows the interactive manipulation of the primary and the final cost distribution. c_i is defined as a 0-1 variable, interpreting the unit value as the existence and the zero value as the absence of the corresponding cost. The (0, 0, 1, 0, 0) vector stands for a situation, where, only c_3 cost incurs, due to air and water pollution (Figure 8). The (0, 0, 1, 0, 1) vector states that air - water pollution cost and energy-water-other resources cost co-exist in the primary cost distribution (Figure 9).

By setting 0-1 values in c_i parameters, the synthesis of the direct cost distribution is defined and, automatically the new developing cost distribution is visualized by a series of grey-shaded squares. Similar cost scenarios could be used in models for any of the three types of settlements, by using the analogous matrix of synergistic cost effects.[7] The generality of the results is assured by making infinite parameters' substitutions with random numbers. An

[7] The computer codes in *Mathematica* are available on request.

analogous computational framework could be considered to examine cost scenarios with different types of industries.

Figure 7: In riverine coastal steeplands, the synergistic mechanism from c_5 cost causes a cost distribution with no cost in human health and in energy, water, other resources

Figure 8: In riverine coastal steeplands, c_3 cost triggers a cost distribution consisting of c_1 c_2 c_4 costs

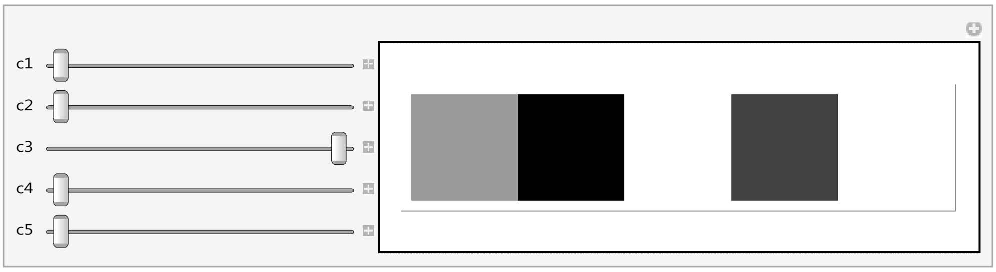


Figure 9: In riverine coastal steeplands, the co-existence of factors 3 and 5 and their dedicated costs triggers a cost distribution consisting of c_1 c_2 c_3 c_4 costs

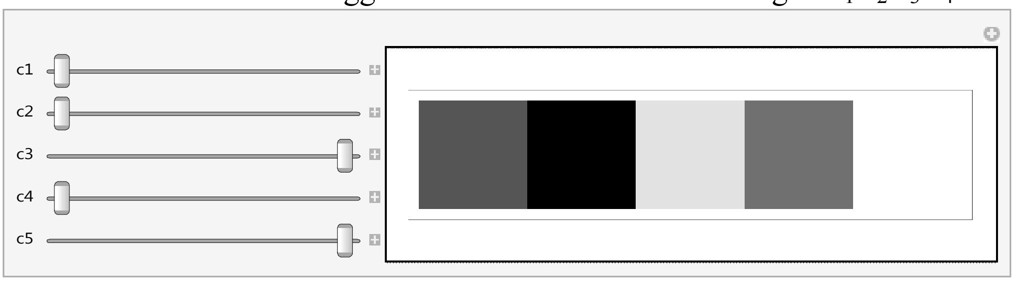
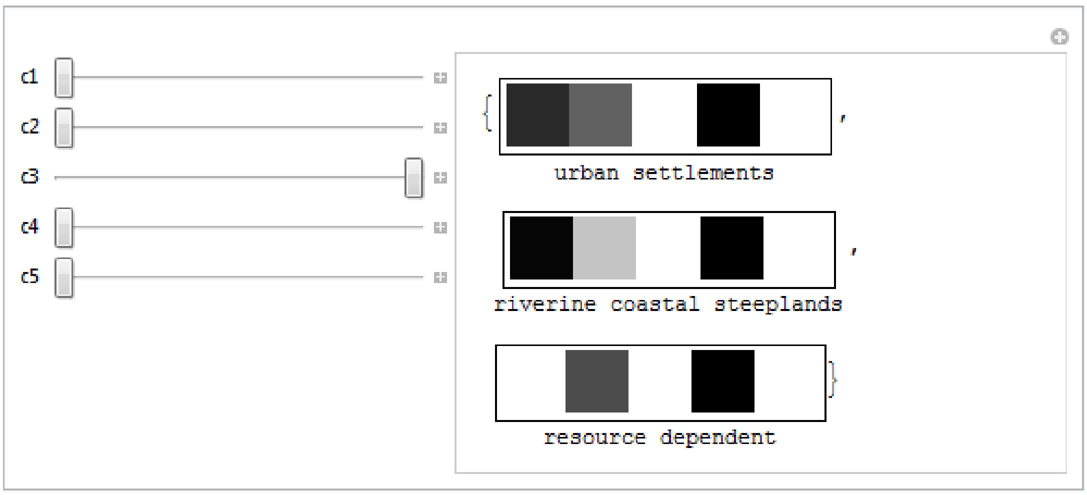


Figure 10: A comparative output



3.1.2 Potential for a Quantitative Study with Cost Scenarios

Our computer codes aim to derive indicative estimates of the potential costs, assuming any possible direct cost scenario. The direct cost scenario is defined using sliding bars that assign values to each cost from a predefined interval (e.g. [0, 10000]). In Figures 11 and 12, we examine how similar direct cost distributions end-up differently in urban and resource dependent settlements, due to the synergistic impact mechanisms. In the output produced the user has also the option to perform sensitivity analysis: moving the sliding bars, the primary cost distribution is perturbed and one can observe the variations of the costs computed in the list on the right part of the window.

Figure 11: In urban settlements, costs in migration and flooding pass to all categories of costs.

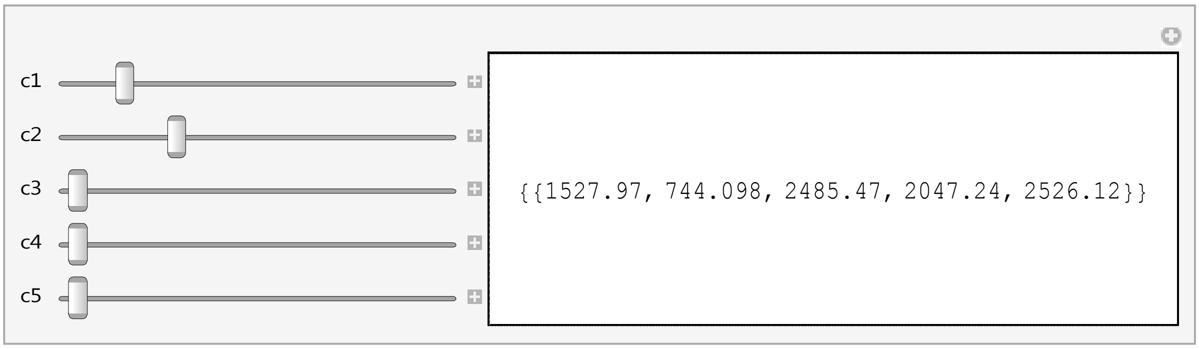
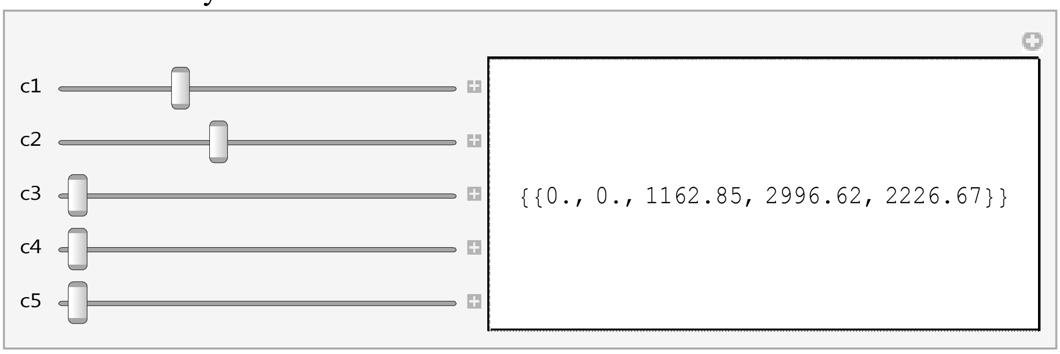


Figure 12: In resource dependent settlements, costs in migration and flooding are extinguished since in the cost variable vector, migration and flooding have steadily zero values.



3.2 Nonlinear Interactions of climate related costs

In the case when climate related costs interact with each other in a nonlinear fashion, the matrix of synergistic cost effects should contain cells with mathematical functions. That is

$$\begin{pmatrix} f_{11} & f_{12} & f_{13} & f_{14} & f_{15} \\ f_{21} & f_{22} & f_{23} & f_{24} & f_{25} \\ f_{31} & f_{32} & f_{33} & f_{34} & f_{35} \\ f_{41} & f_{42} & f_{43} & f_{44} & f_{45} \\ f_{51} & f_{52} & f_{53} & f_{54} & f_{55} \end{pmatrix}$$

Then, our computational approach generates a functional matrix, where f_{ij} functions could be the regression fits estimated from empirical data for every pair of factors (e.g. 25-7 pairs for urban settlements). The nonlinear functions f_{ij} can be specified by nonlinear regression methods.[8] By setting numerical values in the primary costs (m,f,a,h,e), our codes compute the costs after the impact of synergistic mechanism. The sum of each column will give the cost of the corresponding climate related factor.

The *Mathematica* codes for modeling the nonlinear synergistic mechanism and for automatic calculation of costs are presented next. That is:

```
a[i_, j_] := Which[i == 1 && j == 1, 0, i == 1 && j == 2, f12[m], i == 1 && j == 3, f13[m], i == 1 && j == 4, f14[m], i == 1 && j == 5, f15[m],
  i == 2 && j == 1, f21[f], i == 2 && j == 2, 0, i == 2 && j == 3, f23[f], i == 2 && j == 4, f24[f], i == 2 && j == 5, f25[f],
  i == 3 && j == 1, f31[a], i == 3 && j == 2, f32[a], i == 3 && j == 3, 0, i == 3 && j == 4, f34[a], i == 3 && j == 5, 0,
  i == 4 && j == 1, f41[h], i == 4 && j == 2, f42[h], i == 4 && j == 3, f43[h], i == 4 && j == 4, 0, i == 4 && j == 5, f45[h],
  i == 5 && j == 1, f51[e], i == 5 && j == 2, f52[e], i == 5 && j == 3, f53[e], i == 5 && j == 4, 0, i == 5 && j == 5, 0]

Table[a[i, j], {i, 5}, {j, 5}] // MatrixForm

(   0     f12[m]  f13[m]  f14[m]  f15[m] )
( f21[f]    0     f23[f]  f24[f]  f25[f] )
( f31[a]  f32[a]    0     f34[a]    0    )
( f41[h]  f42[h]  f43[h]    0     f45[h] )
( f51[e]  f52[e]  f53[e]    0       0    )
```

4. Potential data sources for empirical applications

Some directions for valuation of climate impacts and appropriate metrics are given in IPCC (2001, par. 7.3.6). Methods and tools for costing impacts and adaptation of extreme events and disasters are analyzed in par. 4.5 of the special report by IPCC (IPCC, 2012a). Economic impacts of climate change are discussed in the report by the European Commission (SWD, 2013).

When studying more factors related to climate change than the ones examined in this paper, the first step is to test the existence of any causal relationships (one way, both ways or

[8] Nonlinear regression analysis is performed with observations modeled by a nonlinear combination of model's parameters either in a bivariate or a multiple regression specification (Seber and Wild, 1989).

irrelevant) using econometric tests like Granger causality test. The methodology to estimate the entries in the matrices of synergistic effects of section 3 is related to statistical methodologies available for the investigation and estimation of cost interactions like correlation or regression analyses.[9]

Empirical applications of the proposed model formulations demand data for appropriate estimates of the primary costs of the five climate related factors under investigation. In the case of Greece and using the settlement and industry types mentioned so far, various databases can be used. Some indicative preliminary guidance (depending on data availability in regional or local level) follows. Specifically:

1. Migration costs can be approximated by the absolute[10] value of the annual population variation (source: http://data.worldbank.org) multiplied by the GDP per capita of the relevant year (source: http://data.worldbank.org). Alternatively various percentages may be assured for the contribution of emigrants and immigrants to GDP.
2. Flooding-landslides-fires costs can be approximated by the compensations due to extreme weather events, available from the General Secretariat for Civil Protection (http://www.gscp.gr/ggpp/site/home/ws.csp)
3. Air Pollution costs can be approximated by multiplying annual CO_2 emissions (kt) (source: http://data.worldbank.org) with the mean value of the allowance price evolution in the EU ETS for a specific time period like 2005-2009[11] or 2009-2013 etc (source: http://www.theccc.org.uk/publication/meeting-carbon-budgets-the-need-for-a-step-change-1st-progress-report/)
4. Human Health costs can be approximated by hospitalization costs of the very young (i.e. <1 year of age), older adults (i.e. those of ≥65 years of age) and immunocompromised

[9] Exploring the issues of synergistic impacts of climate related costs it is important to be clear in the distinction between correlation and causation.
[10] Taking into consideration only the costs associated with migration.
[11] The data set was used to produce the exhibits published in the Committee on Climate Change (2009).

individuals, available by the Hellenic Statistical Authority (http://www.statistics.gr). As Ebi et al. (2006) and Mills (2009) claim these three groups are usually the most sensitive and at the highest risk in terms of health outcomes due to climate conditions as they are quite sensitive to food- and water-borne diseases, present limited capacity to adapt to extreme temperatures and have less ability to cope properly with behavioral changes when they face these extreme temperatures and extreme weather conditions.

5. In the case of access to energy, clean water and other resources we may limit for simplicity to energy costs, which can be approximated by multiplying annual energy use (kt of oil equivalent) (source: http://data.worldbank.org) with oil prices of the relevant year (source: http://ec.europa.eu/energy/observatory/oil/prices_en.htm)

5. Conclusions

Climate related costs are linked through interactions estimated by appropriate impact indicators. Our contribution provides constructs of the matrix with these impact indicators, aiming to represent its structure and trying to define its entries. In a second step, we make matrix economic system models for human settlements and types of industries, to evaluate the costs related to the synergistic environmental effects.

Our proposed models could help decision makers to obtain either the synthesis or the numerical estimate of cost distribution variable vector. To illustrate the results, we build interactive applications in *Mathematica*; we provide instant creation of dynamic interfaces that allow varying parameters and gaining useful insights from datasets. Our computational approach provides a parameter setting for the existence of costs, the amount of costs and the impact indicators of costs. Varying parameters' values, each case study concerning human settlements or industries is examined in a stochastic fashion. The variety and the clarity of the computer output are the models' advantages.

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