Exploring a Fitness Landscape of Environmental Impacts

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Abstract The fitness landscape literature within the Complex Adaptive Systems field highlights the importance of the form of the 'landscape' of possible system states adoptable by an evolving entity. Against this theoretical background the validity and utility of constructing 'Environmental Impact Fitness Landscapes' is hypothesised and explored as a framework for informing the process of sustainable development. A brief analysis of the possible form of such landscapes is presented drawing on empirical evidence from ecotoxicology. While this evidence suggests such landscapes may have multiple optima, critical parameters such as the provision of the feedback necessary for optimisation, the global morphology of the landscape and the number and height of optima remain unanswered. As a basis for further exploration of the idea a modelling framework is proposed based on the Kauffman NK model. The NK model from theoretical biology is a variant of the spin glass class of models developed in physics and is one of the most generic of this type. It allows exploration of entire families of landscapes across a range of sizes and degrees of roughness. The NK framework is introduced along with the modifications required for its use with environmental impact fitness landscapes. Preliminary results exploring the distinctions between the NK model and its modified Environmental Impact Fitness Landscape form are presented and discussed. The paper concludes with a brief exploration of the implications for the process and policy of sustainable development.

Introduction

This paper explores the process, and the implications, of mapping a set of environmental impacts onto a fitness landscape, through the use of fitness landscape theory and a modified Kauffman NK model. Fitness landscape theory, which sits within Complex Adaptive Systems theory and more broadly within the Evolutionary Paradigm, explores the nature of the space of all possible states adoptable by a system. The landscape is formed by allocating each of the system's states a fitness value. Knowledge of the form of this landscape of states is important for two reasons. Firstly, if the system is subject to evolutionary optimisation, the form determines the likelihood of the system reaching its globally optimal state. Secondly, if we are trying to manage a system towards some end, the relationship between landscape form, and our knowledge of this form, largely determines the success of our management venture. Both these points are relevant to the process of reducing environmental impacts from human systems.

The paper takes the following form. Fitness landscapes are introduced through the NK model of tuneably rugged landscapes developed by Kauffman [1993]. The applicability of the NK framework to the modelling of Environmental impact fitness landscapes is then demonstrated. Sufficient empirical evidence is then drawn from secondary sources to demonstrate the likelihood of multiple optima on such landscapes. The modelling of environmental impact fitness landscapes is then gone into in some detail with emphasis placed on the modifications to, and the limitations of, the NK modelling platform. The paper concludes with presentation of preliminary results and discussion of the Environmental Impact Fitness Landscape framework's implications for the process of sustainable development.

The NK Model of Tuneably Rugged Landscapes

While fitness landscape theory is used in many fields including physics, mathematics and computer science, this paper will draw primarily on its use in theoretical biology. Specifically the focus will be on the Kauffman NK model and the associated body of statistical properties of such landscapes developed by Kauffman [1993]; Kauffman and Johnsen [1991]; Kauffman and Levin [1987]; Weinberger [1991]; Weinberger and Stadler [1993] and others. This paper restricts itself to establishing the Environmental Impact Fitness Landscape framework for static landscapes, while acknowledging the potential for the future application of coevolutionary dynamics.

In order for a system to be modelable within the NK framework it must consist of some number of parts each of which can adopt some number of states. Additionally, for any particular configuration of the system it must be possible to define a value of fitness. Fitness can be any property definable as some function of the states of the parts of the system. The state of each part makes a contribution to the fitness of the state of the whole either independently, or as a function of its relations with the states of other parts of the system. Two things must be born in mind here. Firstly, within the NK model as with other spin glasses, the fitness values themselves are drawn at random from probability distributions. The model is therefore stochastic and can not be thought of as a deterministic mapping of interactions among the system's parts. Secondly it is not necessary that fitness be definable internally to the system. In the case of the archetype of such fitness functions, the natural selection of fitter genetic variants, fitness is arbitered externally by the environment. Neither does it matter whether the parameter fitness is to be maximised or minimised. The biological use of fitness landscapes looks to maximise fitness while in spin glass theory the parallel property to fitness, the system's energy, is minimised. Indeed the Levitan/Kauffman implementation of the NK model allows either maximisation or minimisation of the fitness function [B. Levitan *pers. comm.*, 1994].

For such systems an NK fitness landscape may then be constructed. The number of parts of the system, or parameters being modelled, is designated *N*. The number of states adoptable by each part is designated *A*. The number of other parts on which the fitness contribution of an individual part of the system depends is designated *K*. Note that *K* may vary from zero to full interdependence (*N-1*) and that it is the variation of *K* which determines the roughness of the landscape. It follows from this that the system can adopt A^N discrete states. The fitness landscape is then constructed as a hypercube with A^N vertices each being one of the possible states of the system. Each such state/vertex has its associated fitness value. Each state is connected via an edge on the hypercube to every other state to which the system can change through the alteration of one of its parts. As each of the *N* parts can alter through *A* states it follows that each state has *N(A-1)* such neighbours on the landscape. It is this number of neighbours which determines the dimension (*D*) of the hypercube. The parameters N, A & K form the core of the NK model with more detailed analyses building on this.

Environmental Impact Fitness Landscapes

Prior to defining the modelling parameters as they apply in the environmental case it is necessary to distinguish between *impact as cause* and *impact as effect*. The *impact as cause* is an action effecting the environment, for example the level of emission of a given toxin from a production process. These we call perturbations. Impact as effect is the extent to which such actions or perturbations change the overall health of the environment. These we call impacts.

The set of perturbations from a human activity can be viewed as a system which meet the criteria required for NK modelling. Many human activities perturb the environment in a number of ways - let this set of perturbations constitute the system and the number perturbations equal N. Each perturbation can be quantified and be divided into some arbitrary number of levels - let the number of levels be A. It seems reasonable to assume that the cumulative impact of the system is some function of the impact contributions of each of the parts either individually, or in relationship to other parts with which they may interact. This assumption constructs the environment as external arbiter of the gross impact from a system and is precedented by Darwinian model of evolutionary biology. The equating of impact with fitness constructs fitness as a parameter to be minimised, i.e. on environmental impact fitness landscapes going down hill minimises impact. The search is therefore for system states that represent the bottoms of valleys.

Evidence suggesting multiple optima

It is possible to identify several mechanisms capable of giving rise to multiple optima on impact landscapes. Two such mechanisms are direct synergistic or antagonistic interactions between perturbations, and the ability of perturbations to push natural systems between alternate stability configurations. An additional mechanism, present in many such nonlinear interdependent systems, is frustration. Frustration is indissolubly linked to interaction between the system's parts and it is this interaction/frustration phenomena that dominates the form of the landscape.

Within the NK model this interaction/frustration phenomena, modelled by the parameter K, works as follows. Where there are no interactions $K = 0$ and the landscape has a single optima. However where interactions do occur conflicts can arise from the inability of a part to be in two states at once. This can be seen in table 1. The highest fitness available to part 4 requires parts 3 and 4 to be in states 1 and 1 respectively. The highest fitness available to part 5 requires parts 4 and 5 to be in states 2 and 1 respectively. In this instance part 4 would need to be in states 1 and 2 simultaneously in order to minimise overall impact. As it is unable to do so it is said to be frustrated.

Evidence of perturbation interaction can be found in the plant toxicology literature. McCune [1986, p.314] studied the effects on plants of a variable mixture of HF and SO_2. The resulting 'response surface', a two dimensional plot with the concentration of the respective pollutants on each axis, displayed multiple and distinct regions of synergistic and antagonistic interaction separated by additive response contours. If one were to extrapolate this into three dimensions to allow plotting the level of damage, the resultant surface would have multiple impact peaks corresponding to different concentrations of the pollutants. Runeckles [1984] cited the work of numerous others working with SO_2/O_3 interactions; SO_2/NO_3 interactions; and O_3/heavy-metal interactions as appearing to fit similar response surfaces.

Assuming gross ecosystem fitness is some function of the impacts on individual ecosystem components, then synergistic or antagonistic interaction of perturbations as measured against the health of a component should give rise to similar effects at the ecosystem level. Accepting the possibility of interaction between perturbations it follows that frustration related effects may also be a determining factor in the form of the landscape. Given evidence of this joint interaction/frustration phenomena it seems reasonable to adopt a model with the capacity to vary the extent to which such effects determine the form of the landscape. The NK model provides this capacity.

TABLE 1 [After Weinberger 1993]

A representation of the basic NK model (clear cells) and modifications for application to Environmental Impact Fitness Landscapes (shaded cells).

The parameter fitness is defined as impact and is replaced by that term.

Model parameters A = 3, N = 8, K = 1 for the interactive component of impact and X = 0.5.

Interaction is assumed to be with each part's left neighbour with part 1 interacting with part 8 to produce periodic boundary conditions.

Table 1.1a

No. of part	1	2	3	4	5	6	7	8
State of part	1	2	0	2	1	1	0	2
Interactive impact component (From tables below)	0.38	0.88	0.62	0.81	0.98	0.96	0.24	0.43
Interactive impact ($I_{(i)}$) of system in the above state (defined as average of the fitness contribution of the individual parts) = 0.66								

Table 1.1b

Additive impact component (From tables below)	0.47	0.91	0.21	0.79	0.88	0.52	0.13	0.55
Additive impact ($I_{(a)}$) of system in the above state (defined as average of the fitness contribution of the individual parts) = 0.56								
Gross impact of system in the above state (defined as X % of ($I_{(i)}$) + (1-X)% of ($I_{(a)}$) Where X is a modelable parameter) = 0.61 (for X = 0.5)								

Table 1.2

Tables for interactive impact calculation of parts 4, 5 & 6. Other parts calculated in similar manner (tables not shown).

K = 1 Interactive impact table for part 4			K = 1 Interactive impact table for part 5			K = 1 Interactive impact table for part 6		
Part 3	Part 4	Impact of part 4	Part 4	Part 5	Impact of part 5	Part 5	Part 6	Impact of part 6
0	0	0.03	0	0	0.44	0	0	0.39
0	1	0.93	0	1	0.73	0	1	0.36
0	2	0.81	0	2	0.10	0	2	0.56
1	0	0.16	1	0	0.69	1	0	0.98
1	1	0.98	1	1	0.70	1	1	0.96
1	2	0.79	1	2	0.19	1	2	0.90
2	0	0.24	2	0	0.47	2	0	0.30
2	1	0.61	2	1	0.98	2	1	0.68
2	2	0.99	2	2	0.61	2	2	0.40

Table 1.3

Tables for additive impact calculation of parts 4, 5 & 6. Other parts calculated in similar manner (tables not shown).

Additive impact table for part 4		Additive impact table for part 5		Additive impact table for part 6	
Part 4	Impact of part 4	Part 5	Impact of part 5	Part 6	Impact of part 6
0	0.23	0	0.07	0	0.46
1	0.59	1	0.88	1	0.52
2	0.79	2	0.91	2	0.73

Gross impact is split into interactive (clear) and additive (shaded) components. For the additive component K = 0. For the interactive component $1 \leq K \leq (N-1)$. Each component generates fitness tables with ($A^{(K+1)}$) entries for each part. For each component the impact contribution of each part is determined by reference to the impact table for each part. The state of the part in the additive impact tables, or combination of states of parts in the interactive impact tables, indexes the part's additive or interactive table returning the corresponding impact value. The additive and interactive impacts of the system's state is defined as the average of the part's contributions. Gross impact of the system's state is a function of the weighting (X) placed on the relative contribution of the additive and interactive components of impact. X becomes a new parameter of the model.

Modelling

In *The Origins of Order* Kauffman [1993 p.40] introduces the NK model as "...a simple formal model of rugged fitness landscapes..." which can, as he subsequently shows, "...be interpreted as a model of genetic interactions...". Per Bak [1993] has interpreted the NK model as a spin glass, using it to explore self-organised criticality. In this context we are interpreting it as a model of environmental perturbation interaction and in doing so will introduce some minor variations to tailor its use to this context.

The following explanation of the model refers to its representation in table 1. Initially consider the unmodified NK model (clear cells). In this the impact values in the part's fitness tables are drawn independently and randomly from a uniform distribution between 0 and 1. In this case the system state consisting of all 0 part states should be no more or less likely to be fit than the system state consisting of all A part states. This is appropriate where the states of the parts have no discernible correlation with fitness. In the environmental impact fitness landscape context however, it seems reasonable to assume that there is a broad correlation between an increase in the level of intensity of perturbations, and an increase in gross impact. Such a correlation introduces a global form to the landscape. This global form is distinct from the degree of local roughness caused by the interaction/frustration phenomena.

The distinction between local and global form is achieved by dividing impact into interactive and additive components. The interactive component (Table 1.2) is modelled by variation of $1 \leq K \leq (N-1)$. The additive component (Table 1.3) is modelled by N impact tables in which K = 0. These are sorted by impact from lowest to highest. Setting K equal to 0 produces a landscape with a single optima while sorting by impact ensures that state (0_1, 0_2, 0_3 ... 0_N) is the global impact minima, while state (A_1, A_2, A_3 ... A_N) is the maxima. This brings the model in line with the expectation that perturbation intensity is broadly correlated with impact.

The gross impact of any system state is then defined as the sum of X percent of the additive impact and 1-X percent of interactive impact. Variation of the parameter X varies the ratio of additive to interactive impact and consequently the ratio of global to local structure.

Results

The act of distinguishing between additive and interactive components of the landscape separates Environmental Impact Fitness Landscapes from the standard NK model and dictates the first area of exploration of the Environmental Impact Fitness Landscape framework. One of the unexpected features of the NK model is the presence of what Kauffman termed a "Massif Central" on the landscape [Kauffman 1993, p.60]. This Massif Central refers to the observation that, for low values of K, the highest optima on the landscape are clustered together. This is counter intuitive given the random nature of fitness allocation to the states of the system's parts. Kauffman cites its presence for A equals 2 landscapes but does not say whether this phenomena persists for higher values of A. Determining whether it is present for higher values of A is important within Environmental Impact Fitness Landscape framework for two reasons. Firstly, within this framework the number of states A is a discrete representation of a continuous variable therefore it is the behaviour of the system as A approaches infinity that is of interest. Secondly, the additive component of this framework gives global form to the landscape. Were the interactive component to produce a global form as well, the interaction between the two would require exploration. In order to explore this aspect of the model's behaviour a set of scatter graphs of increasing A showing landscape optima fitness versus distance from the fittest optima found are constructed (figure 1). On these graphs the Massif Central effect should skew the scatter pattern into a pronounced diagonal leading out from the origin. The construction of such graphs requires a definition of distance on the landscape. Within biological fitness landscape use the common measure is Hamming Distance. In this context this is the number of parts which differ in state between the highest optima found (the datum) and other optima. This however is only defined for the two state case (A = 2).

To explore values of A greater than 2 this has been modified as follows:

$$H_{Mod} = (H-1) + \frac{(\sum_{n=1}^{N} S_{O_D}^{n} - S_{O_i}^{n})}{(A-1)}$$

Where:

H_{Mod} = Modified Hamming Distance

H = Hamming Distance as defined above

N = The number of parts in the system

$S_{O_D}^{n}$ = The state of part n of the highest optima found

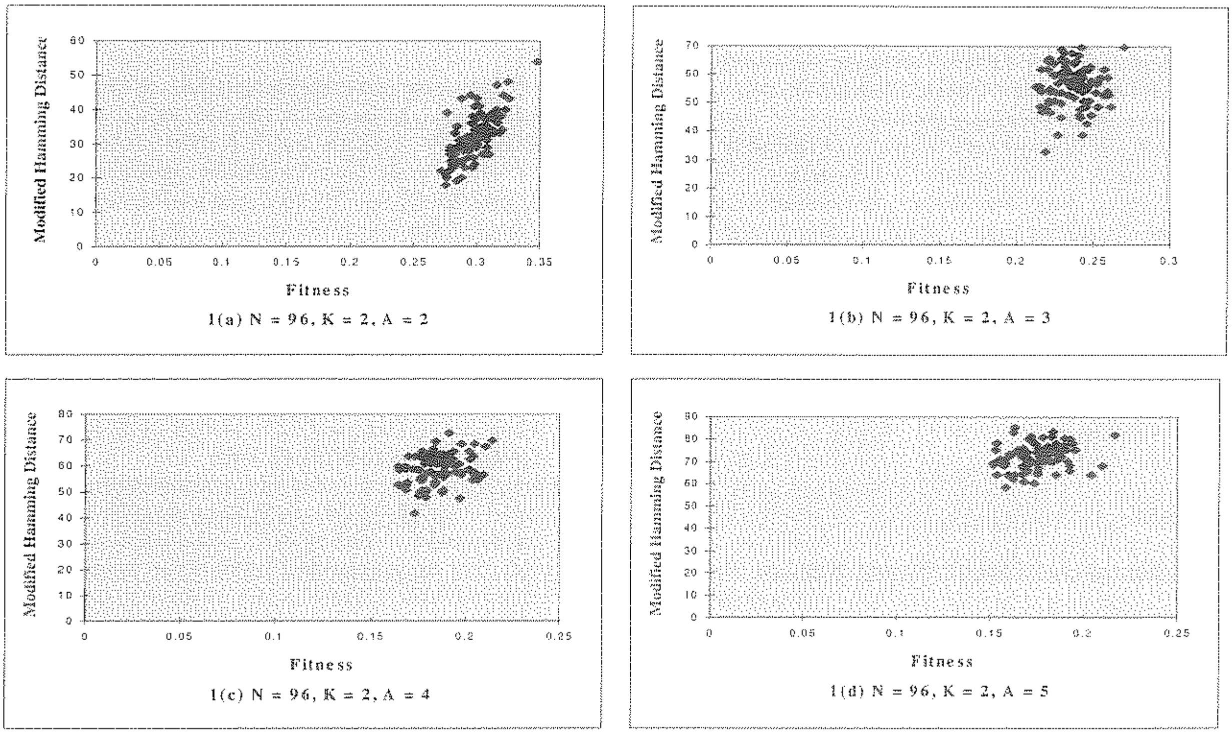
$S_{O_i}^{n}$ = The state of part n of the local optima for which the Modified Hamming Distance is being found

A = The number of states adoptable by the part.

This reduces to the standard definition of Hamming distance where A = 2.

For the use of this definition of distance on the landscape the A = 2, K = 2 case appears to shows some evidence of a Massif Central however the effect seems negligible for A greater than 2. This must be qualified by highlighting the role of the definition of landscape distance in detecting such an effect and the small range of A within which this effect has been searched for. Computational time and power ultimately limits the range of A within which such effects can be looked for as run time scales exponentially with A.

In the absence of a Massif Central effect for A greater than 2 landscapes the need to address the interaction of global forms arising in both the additive and interactive components of Environmental Impact Fitness Landscape's is obviated.



1(a) N = 96, K = 2, A = 2

1(b) N = 96, K = 2, A = 3

1(c) N = 96, K = 2, A = 4

1(d) N = 96, K = 2, A = 5

Figure 1 - Set of scatter graphs of increasing A. Each graph shows the optima found from 100 walks from random initial positions over the same landscape. Optima are plotted against their fitness and their modified hamming distance from the highest optima found. The Massif Central effect, if present, should skew the scatter pattern into a pronounced diagonal leading out from the origin.

Optimisation on Environmental Impact Fitness Landscape's

In order for the Environmental Impact Fitness Landscape framework to inform the process of sustainable development the impacting system must be able to optimise. For this the system requires feedback as to its location on the landscape and information on local and/or global landscape form. The provision of this feedback is what many see as the central issue in the process of sustainable development [Naveh 1986, p.343 & 346.].

In the biological case there is an indirect but strong feedback mechanism between genotype and landscape mediated by the phenotype. The system, a population of similar genotypes, gains information about landscape form through the process of mutation and natural selection. The process is therefore heuristic, indirect, usually local and done in an environment in which strongly selects the parameter being optimised.

In the Environmental Impact Fitness Landscape case this mechanism is currently inapplicable. There are four primary reasons for this. Firstly impacting systems are not currently selected on the basis of minimal environmental impact. Selection and propagation of the products of such systems is more usually a function of utilitarian and economic factors. Secondly our knowledge of the effects of individual impacts is limited, and where systems of interacting impacts are concerned almost negligible. Thirdly inherent systemic uncertainties, such as those highlighted by Harwell and Harwell [1989 p.524] arising from insufficient data, extrapolation from existing knowledge, unforeseeable indirect effects and environmental stochasticity, intrinsically limit our knowledge of, and predictive abilities for, such systems. Fourthly our knowledge of such systems is fixed in the intrinsically irreversible time/history of complex systems evolving through points of bifurcation [Timmerman 1986, p.436], this brings into question the usefulness of historical information as a guide to future events. The danger in the use of historical information is of course amplified in times of rapid systemic change. For these reasons there are inherent difficulties in the optimisation of gross environmental impact.

There appears to be no neat solution to the provision of the feedback necessary for optimisation over the impact landscape. It is however possible to explore the issues surrounding optimisation through the imposition of what may be termed a 'meta' landscape. This meta landscape is simply the best available knowledge as to the form of the impact fitness landscape. Constructing this meta landscape separately makes distinct our current state of knowledge from the subject of such knowledge. Making this distinction is rationalised within, and dictated by, the evolutionary paradigm. The meta landscape suffers from all the sources of informational uncertainty outlined above resulting in inevitable quantitative and even qualitative mismatches between itself and the actual impact landscape. Holling [1986], Timmerman [1986] and Casti [1992] all argue such mismatches are inevitable in Complex Adaptive Systems due to their potential for extreme sensitivity to initial conditions. These mismatches lie at the base of the notion of surprise and it is the acceptance and integration of inevitable surprise that is one of the key distinctions between the Newtonian and the Evolutionary paradigms. Thus the introduction of the state of our knowledge as a separate and distinct landscape within the Environmental Impact Fitness Landscape framework makes explicit and embraces the inevitable uncertainties involved in managing complex adaptive systems.

While these systemic uncertainties may ultimately place a limit on the level of resolution of landscape form, it is expected that there would be considerable scope for improving the current level of understanding through further research into the effects of impacts individually and in interacting systems, both with, and within, the environment. In the face of such local uncertainties a scale of resolution needs to be sought at which the form of the landscape can be determined with some level of confidence. Optimisation may then be possible by providing feedback mechanisms operating at this level of resolution.

Conclusion

The Environmental Impact Fitness Landscape framework highlights the importance of four key mechanisms in the process of sustainable development. Each of these mechanisms then has implications for both policy and the direction of further research.

1) The role of interactions between impacts both with and within the environment. From this arises a natural set of questions regarding the relative weighting of the additive and interactive components of impact, the number of such interactions, and the implications for landscape form arising from the action of frustration on these interactions.

2) The provision of specific feedback mechanisms between impacting systems and their environment. This requires research aimed at increasing our level of understanding of the form of such landscapes and provision of feedback mechanisms tailored to this level of understanding.

3) The provision of incentive to use this knowledge to reduce gross impact. Several mechanisms exist for the provision of such incentive including: legislation; the progressive integration of environmental externalities into the economic considerations of impacting systems and; the increasing of environmental awareness through public education.

4) Acceptance of uncertainty and the development of mechanisms to deal with it. This focuses attention on the further development of the Precautionary Principle and on the probabilistic methods best able to determine the risks involved.

While alternate approaches address some of these issues Environmental Impact Fitness Landscape's offer a conceptual framework within which many of the contemporary issues of sustainable development may be brought together. Importantly it is a framework that actively embraces the uncertainties of what it seeks to understand, and in doing so may avoid the pitfalls of some of its more deterministic brethren.

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