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The carrying capacity imperative: Assessing regional carrying capacity methodologies for sustainable land-use planning

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Abstract
While some existing carrying capacity methodologies offer significant insights into the assessment of population carrying capacities, a comprehensive model is yet to be developed. This research identifies, examines and compares a range of methodological approaches to carrying capacity assessment and considers their relevance to future spatial planning. A range of key criteria are employed to compare various existing carrying capacity assessment models. These criteria include integrated systems analysis, dynamic responses, levels of risk, systemic constraints, applicability to future planning and the consideration of regional boundary delineation. It is suggested that by combining successful components from various authors, and collecting a range of interconnected data, a practical and workable system-based model may be achievable in the future.

Keywords
carrying capacity, population, resource depletion, sustainable land-use, spatial planning

Introduction
It is widely recognised that the global impact of an ever-increasing population, combined with dangerously depleted natural resources highlights the urgent need for humanity to live within the carrying capacity of its natural assets. However, little attention has yet been given to locally quantifying these assets, nor to accurately determining when we are living within or beyond the resources of a particular area of land. Carrying capacity assessment helps to facilitate this process. It not only calculates optimal population numbers but ideally prompts equitable and sustainable land-use outcomes in accord with naturally determined limits. The carrying capacity imperative is an environmental and ethical initiative of vital future importance. In fact, it is an imperative on which society's very survival may well depend.

Background
The question of global overpopulation has challenged the world's demographers since Thomas Malthus raised the prospect over 200 years ago. Malthus argued that while human population potentially grows exponentially, the resources required for human survival remain relatively finite. To date, society has largely managed to produce the resources necessary to feed, house and clothe the majority of the earth's inhabitants, though in vastly differing degrees of comfort, and Malthusian sceptics argue that his predictions of overpopulation have not eventuated because advanced technology and the use of high-energy fossil fuels have allowed for a significantly expanded resource-base (Cohen, 1995, p.37). However,

this mode of industrialised production and consumption has proven costly, with social dislocation, economic inequities and environmental degradation becoming global problems.

A revision of current energy-intensive consumption patterns is now essential in order to both redress societal inequities and also because the very resources needed to allow the global system to function, such as fossil fuels, fertile soils, fresh water and fossil-fuel-based fertilisers, are rapidly depleting (Pimentel and Pimentel, 2004, p.1).

New land-use strategies need to be developed in order to cope with the challenges ahead. A re-localised system of resource usage is one potential systemic change that may facilitate more sustainable future lifestyles. For instance, Vail (2006) argues that local production and consumption of resources engenders greater environmental and ethical responsibility in local populations because impacts are often more immediately obvious and behavioural correctives, more willingly undertaken. To ensure more equitable and sustainable future land-use patterns we must directly link and limit populations to the regions which sustain them. This invokes a crucial ethical responsibility, referred to here as the carrying capacity imperative, with immense implications for the future of political, economic, educational and planning theory and practice. Carrying capacity assessment (CCA) determines the maximum number of people that can be supported indefinitely in a given location without causing environmental degradation. The concept establishes direct causal relationships between a specific landscape, timeframe and people, and inherently links these aspects to systems of land usage and social function.

There have been several attempts to quantify carrying capacity populations for certain land areas but the complex nature of modern lifestyles has complicated the process. For instance, in a globalised world, this form of resource accounting has presented methodological difficulties because resource production, consumption and waste assimilation are often spread across vastly differing demographic and geographic landscapes. In other words, international trade has warped the potential reliability of CCAs. However, given compelling evidence of forthcoming resource depletion and the restrictions imposed by climate change, the question must be asked: is it desirable, or even feasible, to perpetuate the existing highly energy-dependant globalised system of trade? If a less energy-intensive, more localised and reasonably self-reliant social configuration was adopted, how can practical planning methods, such as CCA, be activated to help guide this transition?

This research has aimed to identify, examine and compare existing approaches to CCA methodology and theoretically considers their relevance to future spatial and infrastructure planning. It raises the following questions: which CCA methodologies are best suited for determining future sustainable land-use and community infrastructure? What gaps in existing research need to be addressed? Is it possible to achieve a practical model for assessing regional human carrying capacity?

Sustainable lifestyle patterns need to be adopted that limit environmental degradation and also provide the resources necessary for human wellbeing. This would inevitably imply an integrated systems design process encapsulating social, economic, political and environmental considerations. To this end, CCA methods that accord with whole-system design approaches need to be developed that can be applied to any given land area to inform planners, stakeholders and local inhabitants on sustainable land-use options.

Criterion-based comparison of methodologies

There appears to be no widely accepted methodological approach to the assessment of human carrying capacity. The complex nature of this task has led researchers to incorporate various societal and environmental parameters in a number of different ways and with varied degrees of accuracy and insight. For instance, while current carrying capacity-focused literature covers various global propositions, few proponents have focused on regional implications. While several current models centre entirely on existing societal configurations, an ideal CCA model should also consider alternative future lifestyles and incorporate safe and sustainable population thresholds for forward planning purposes. Cohen (1995, p.359) describes well-designed CCA models as a balance between human choices and natural constraints. Many criteria for CCA assessment used in this research are based on Cohen's hypothetical ideal model. As such, a best-practice CCA model should:

1. Allow for choice in underlying integrated systems, including political and economic institutions, technology, demographic arrangements, environmental conditions, moral values, plus levels and distribution of societal wellbeing.

2. Allow for choice in cultural habits such as diet, fashion, taste and tradition.

3. Proffer dynamic responses allowing for various timeframes and random variation.

4. Assess levels of impact and risk.

5. Consider constraints in resource systems (e.g. food, water, energy, soil, minerals, forests and fertiliser); spatial systems (e.g. land-use); biological systems (e.g. biodiversity, disease, waste/assimilation); climatic systems (e.g. climate change, rainfall, seasonal variations).

6. Check for inconsistencies and suggest alternatives by prompting users to resolve problems and contradictory choices.

7. Contain credible and empirically tested data drawn from relevant sources.

8. Offer simple and intelligible usability and adapt to various locations and populations.

9. Be applicable to long range future-oriented land-use planning.

10. Consider fine-grained scale analysis and methods for defining localised boundaries.

11. Recognise people's relationship with and responsibility to their natural environment by the restoring and reserving of natural habitat and wildlife areas.

CCA methodologies—existing range

An assessment of current carrying capacity literature suggests that methodological approaches can be categorised into three basic typologies—societal, environmental and systems approaches.

Societal CCA methodologies

CCA analyses based primarily on societal parameters are largely extensions of demographic or economic models and are generally quite limited in their scope. Some researchers, such as Wetzel and Wetzel (1995) and Barbier and Scoones (1993) expand their parameters to also include some environmental factors, but ultimately their carrying capacity calculations extend from an economic viewpoint. While societally constraining CCA models may shed light on demographic population limits, they largely ignore the finite nature of the physical environment within which society exists.

Paul Summers', Population Carrying Capacity in Noosa Shire (2004) provides one example of a societal methodology which is applied at a regional scale, in Queensland, Australia. This report compares the population data of the 2001 Australian Census with Noosa Shire's Draft Integrated Planning Act to arrive at a total resident and visitor population carrying capacity of 61,350 people. Summers (2004, p.24) states that this study should be used to "gauge both the needs of the community for the future and importantly, the ability to cater for those needs" by estimating the size and timing of services and infrastructure requirements relating to water supply, sewerage, roads, parking and community facilities.

Given that Summers' aims are demographically based rather than resource-driven, it makes sense for cadastral boundaries to delineate small regions within the Noosa Shire. This is achieved by breaking the Noosa Shire into 82 smaller spatial collections districts (CDs) and calculating the maximum population yield per CD based on existing development guidelines. However, Mochelle (2006b, p.11) argues that the demarcation of spatial boundaries merely in accordance with statistical interests can lead to problems over time as they inevitably change with population fluctuations, various developmental imperatives and government planning schemes. Summers' study is also short-sighted in numerous other ways. For instance, the only systemic parameters and constraints analysed are cadastral and demographic in nature. No references are made to the cultural habits and lifestyle choices of Noosa Shire's population; and while Summers (2004, p.23) acknowledges that population growth cannot continue unchecked, "without a decline in the quality of the environment," he fails to actually measure any such environmental qualities.

Summers' study does take an important step in beginning to link local government planning guidelines and infrastructure commitments to societal limits. Other successes include a reasonable degree of legibility, a reliable foundation of credible data and a suitably small-scale approach. However, the limitations of this study stem from in its narrow field of view—it only assesses population sizes based on existing lot configurations. In merely addressing a demographic issue Summers neglects to ascertain whether the region is capable of providing the resources necessary for its population and fails to consider the environmental impacts of even current consumption patterns, let alone any potential future lifestyles choices.

Environmental CCA methodologies

The majority of existing CCA methodologies focus primarily on the environmental constraints of resource consumption and/or environmental impacts to determine population limits. The most common examples of environmental modelling are based on the Ecological Footprint approach developed by Rees and Wackernagel in the 1990s. This methodology uses both consumption and impact estimates of a particular human population to calculate total land requirements. However, this land is not actually attributable to one specific locality, but is more a generalised estimate of the amount of land required. Exponents of this approach include Cole and Sinclair (2002), Bicknell et al. (1998), and Parker and Selman (1997). Other authors who have developed their own methodology but concentrate more on environmental impacts than resource availability include Mwalyosi (1991), Graymore (2005, p.262), Graymore et al. (2009) and McConnell (1995). A third group of environmental-based analysts focus primarily on the availability of resources, particularly food, energy and water, attainable within defined land areas to derive their CCA calculations. For instance, Cohen (1995, p.402) lists no fewer than 50 such proponents throughout recorded history who have derived global population capacity estimates ranging from one billion to one thousand billion people. More clearly defined and recent examples include Gutteridge's (2006) CCA of Southeast Queensland and Fairlie's Can Britain Feed Itself? (2007). Both these authors comprehensively analysed the diet and lifestyles of their respective populations to derive a total population limit for each defined area of land. While Fairlie's approach to CCA is a quite narrowly focussed on British food production, the processes he employs are methodologically illuminating. He proposes six separate agricultural approaches by which to test the question of whether Britain can feed itself and the answer in each case is in the affirmative.

While Fairlie's study falls short of addressing all relevant system considerations required for reliable CCA, he does begin to approach various aspects of the problem at their most basic level. Certainly, by extrapolating data based on various agricultural systems of production, he has highlighted a worthwhile strategy for possible future methodologies. Fairlie examines production rates from three agricultural systems: conventional chemical-based farming, organic farming and an integrated permacultural approach. The key difference between organic and permaculture systems is that organic farming more or less replicates a conventional system but replaces chemical fertiliser with green manure and crop rotation (allowing periods for fallow ground), while permaculture assumes a high degree of local self-reliance, nutrient recycling (such as human waste), intercropping and mulching (instead of ploughing). Although chemical farming is currently the norm and organic farming, an existing alternative, according to Fairlie (2007, p.20), neither leads to dramatic systemic changes in patterns of land-use, technology, societal institutions and demographic arrangements. In fact, he argues that a broad adoption of a vegan diet using chemical fertilisers might actually reinforce existing urbanisation trends by more easily supporting large centralised populations. However, Fairlie's (2007, p.22) examination of permaculture as a possible future agricultural system led him to various alternate system-based scenarios. For instance, he suggests that some of the measures incorporated into this system would require, “a change in our land management systems, and also in human settlement patterns”, and might lead to a more localised economy integrated with natural processes.

Diet plays a key role in the methodology developed by Fairlie. He compares vegan and meat diets across all three agricultural systems and finds that the introduction of meat dramatically decreases population carrying capacities. Interestingly, the difference in land requirements of meat to non-meat diets is less dramatic in organic and permaculture systems because the livestock play more than one role in the system such as providing fertiliser, fibre and milk; apart from just supplying meat. Fairlie adopts a simple British diet based more on food groupings than the products themselves. He also apportions each food group a daily per person caloric value, then sums daily per capita intake and sources data on equivalent land-use requirements. Generally, this is a common approach to food-constrained CCA calculations and while the level of detail in this study is limited, the technique of altering the variables (i.e. meat versus non-meat diets) is instructive. However, a more detailed analysis of diet, such as that by Gutteridge (2006), would perhaps have yielded results more closely aligned with the actual population in question.

Dynamic, real-time analysis is not present in this study, but Fairlie (2007, p.19) does compare the carrying capacity of Britain in 2005 (with conventional farming and a meat-inclusive diet), to that of 1975. He finds that over the 30-year period, crop yields have risen and that, “the same diet for 14 percent more people can now be provided” on less arable land. So, while there is some retrospective analysis, there is little forward projection of figures. Concerning feedback between parameters, there does appear to be some consideration for how one element within a system might affect another. For example, Fairlie found that livestock within a permaculture model was the key driver in determining degrees of system integration. He subsequently experimented with elements such as stocking rates, animal type (e.g. beef, pig, sheep, chicken), inputs (e.g. feed from pasture, grain or scraps) and outputs (amount of meat required in diet) to devise ways of maximising productivity.

Fairlies's study uses the constraint of land requirements for food production as the predominant limiting factor in assessing Britain's carrying capacity. Minor reference is given to a possible future “energy descent” (Fairlie, 2007, p.22) necessitating an increased dependence on renewable resources but the implications of this are explored only in terms of food and bio-fuel production. Aspects such as climate, water availability, and biodiversity are barely mentioned and while determinants of soil fertility such as nitrogen and phosphorous are briefly discussed, they do not figure directly in the CCA calculations.

Fairlie (2007, p.26) points out that non-conventional farming methods are likely to support a lower population than chemical-based production because yields are lower and, “more land is required to capture nitrogen either through green manure or through livestock.” Given future population pressure, Fairlie suggests that farming approaches may be dictated more by necessity than doctrine with chemical-based farming likely to adopt some organic practices and organic farmers forced to occasionally rely on available chemicals. However, he neglects to address long-term availability of these fossil-fuel-based chemical fertilisers.

In developing an environmentally orientated CCA model, Fairlie, concentrates more on resource availability than on environmental impacts. This is the inverse of most ecological footprint analyses based on the work of Wackernagel and Rees (1996). Fairlie (2007, p.18) states that the aim of his study is to ascertain land-use requirements in non-conventional agriculture given that the UK may have to become more self-reliant in the future. To a limited extent he is successful, but Fairlie readily admits that this CCA study is far from comprehensive, describing it as a, “rough guide, and a useful framework for thinking about such matters.”

System-based CCA methodologies

System-based CCA methodologies not only examine a number of concurrent factors effecting population limits but also consider the relationships between these factors. One of the first of these models was developed by the Club of Rome in 1972 and formed the basis of their publication, The Limits to Growth (Meadows et al., 1972). While Beder (2006, p.13) argues that this seminal work, for the first time, highlights the incompatibility of population growth and resource availability, according to Fearnside (1986, p.73), it focuses on instantaneous rather than sustainable CCA methodologies. Fearnside, developed his own CCA model in Human carrying capacity of the Brazilian rainforest (1986) which examines interconnected relationships in resource usage over extended timeframes. While Fearnside seems to have developed the most comprehensive systems model to date, other proponents of this approach include Mochelle (2006a), Van Den Bergh (1993) and Haraldsson and Olafsdottir (2006). Fearnside uses computer simulations to estimate human carrying capacities for a particular Brazilian rural settlement. Rather than producing specific carrying capacity figures, he generates graphs showing the likelihood of system failure given certain population numbers.

Human carrying capacity of the Brazilian rainforest is a focused study of one settlement area extending about 15 km wide and 30 km long. Data was extensively gathered in the field by researchers visiting the occupants of 165 lots covering 70% of the study area and factors such as consumption patterns, demography, land-use decisions, soil structure and agricultural yield history were compiled over a period of eleven years. Local inhabitants were interviewed, local conditions recorded, climatic data sourced and laboratory analyses made. Once sufficient data was collected, a computer simulation program (titled KPROG2) was created to run simulation studies.

Fearnside's approach provides valuable insights into system-based CCA modelling. Firstly, he incorporates demographic variables such as geographic distribution, age structure, rate of growth, and absolute size; although it is not immediately obvious how these are all integrated into the long-term carrying capacity analysis. Secondly, financial projections are also modelled in this study, with particular emphasis given to the problem of debt. Fearnside (1986, p.118) explains, “[t]he existence of debt poses a constant threat to colonists. When a debt extends over eight or twenty years, it appears a virtual certainty that a crop will fail at least one of those years,” leading to financial failure. Lastly, variables based on technological change are limited in Fearnside's approach, but there is the ability to account for improved seed varieties (by altering base yields) and varied land-use patterns (e.g. annual crops, perennial crops or livestock). Fearnside (1986, p.155) contends that, “in addition to its system orientation, modelling carrying capacity focuses attention on the reality of limits dispelling the illusion that infinite resources and agricultural potential exist.”

The approach of this Brazilian study can be described as a threshold-based, risk assessment employing multiple limiting factors including environmental degradation (e.g. proportion of land cleared, soil fertility) and individual consumption (e.g. caloric and protein intake, cash requirements). Fearnside's (1986, p.79) model bases its CCA output not on a single population figure but on a “gradient of probabilities of failure” over a long timeframe. He explains (1986, p.79), “[t]he maximum acceptable probability of colonist failure, as well as the criteria for failure, can be chosen in accord with socially-defined values.” Environmental degradation is also an integral part of Fearnside's model. Rather than measuring environmental impacts on the overall landscape, Fearnside (1986, p.84) suggests it is more accurate to, “allow an area to be viewed as a patchwork of differently classed subareas to which different standards of permissible degradation apply”.

Fearnside (1986, p.71) advocates long-term sustainable CCA models as opposed to what he describes as instantaneous equations dealing with only limited, non-iterative variables. This philosophy is evident in his modelling of up to 25 years in the future, and various examples of comparisons over a number of timeframes. Random variability is also a key aspect of Fearnside's (1986, p.238) approach. In many cases, he makes calculations based on both deterministic (no random variables) outcomes and stochastic responses, which include, “the effects of random variation in one or more factors”.

While all relevant data is cross-referenced in the calculation of carrying capacities, Fearnside chooses to illustrate the results on a constraint by constraint basis. It is then possible to compare limiting factors to ascertain possible vulnerable aspects of the proposed system. Limiting factors include soil quality (testing phosphorus, carbon, slope, clay content, pH, nitrogen, depth and moisture), climatic relationships (weather patterns, land usage, soil erosion and rainfall), and crop yields (including regression due to loss in fertility, planting density, intercropping, disease, germination rates, pests and spoilage) (Fearnside, 1986, p.123).

Fearnside considers his analysis to be more of a simulation than a model. It uses mathematical equations which replicate relationships in the system, in order to learn more about the real world. One of the key advantages of stimulatory analysis, according to Fearnside (1986, p.87), is the ability to learn from feedback, iteration and testing alternative scenarios. Two types of feedback are accommodated—positive feedback, where existing trends are reinforced, and negative feedback where variable oscillation is dampened (Fearnside, 1986, 90). The simulation is viewed as a continuous long-term process rather than a singular momentary event and, “there is feedback of the information gained from the study to the generation of new ideas, which will in turn be winnowed through the process of testing either by manipulating the system itself or by simulation” (1986, p.92). As such, feedback occurs both within the simulation and between the simulation and the real world but it remains unclear how any clashes in contradictory feedback might be treated within Fearnside's system.

The model in this Brazilian study processes complex arrays of data but unfortunately, it appears that the output is equally complicated. While the use of charts does help in visual legibility, the sheer number of possible graphs and the varied manner in which they are presented makes it difficult for the reader, and most likely, the user, to easily grasp the significant implications imbedded in the detail. Some of the resultant modelling also seems to deviate from expectations but Fearnside, 1986 P. Fearnside, Human Carrying Capacity of the Brazilian Rainforest, Columbia University Press, New York (1986).Fearnside (1986, p.139) is able to explain some of these as local idiosyncrasies and discount other aspects as unimportant. Nevertheless, it appears that some of the detailed modelling parameters such as pH as a predictor of crop yields could be improved.

Fearnside's modelling of optimal population numbers considers both the minimal and maximal limits. For instance, even though overpopulation is a more frequent global problem, he states (1986, p.79) that, “the probability of failing to maintain adequate consumption standards would increase at very low densities due to the difficulties from lack of infrastructure, cooperation and other benefits of society.” While much emphasis is thus given to demographic delineations, little attention is paid in this study to the merits of existing spatial boundaries, despite Fearnside (1986, p.155) admitting that, “land tenure patterns are inseparable from carrying capacity”.

This study (1986, p.52) pays significant attention to the regional environmental qualities of the Brazilian rainforest. He states that, “characteristics of the rainforest ecosystem, changes that occur after it is cleared and planted, and environmental and other considerations”, must be examined, “in planning colonization programs and other forms of development.” He even suggests (1986, p.148) that in some cases, public functions might take precedence over private ownership. For instance, in referring to the retention of natural vegetation, he states that “boundaries of such reserves, once created, must be respected”. While Fearnside's intentions seem admirable, his CCA model provides minimal prompts for the regeneration of natural habitat and only limited concern for the preservation of existing ecosystems.

From the outset, Fearnside (1986, p.77) proposes that, “[t]he purpose of the present study… is to provide an indicator that could be used in development and population planning.” While it seems unlikely that the Brazilian government actually envisaged planning for a resource-deficient future, the isolated nature of this rural project has led Fearnside (1986, p.153) to suggest that the inherent scale of development lends itself to, “self-sustaining communities capable of maintaining their populations at an acceptable standard of living.” Given the assumption that in the future, the production of resources will need to become more localised, perhaps Fearnside's case study serves as a prescient example. By necessity, the local population in this study (1986, p.115) generated 71% of their own caloric food intake and 95% of their own protein.

Fearnside has approached the challenge of CCA modelling in a more thorough manner than most other analysts. The information entered into his KPROG2 program seems to be approaching the level of detail required for accurate results. Variables relating to choices and constraints are integrated into the model and the iterative process of decision-making results in potential real-time, system-based simulations. However, this full potential seems, as yet, unrealised. Consideration should be given to the fact that the software is now over 20 years out of date, but obvious improvements could be made in its usability, legibility and functionality. A more versatile program would also adapt itself to various other locations and gradually become more attuned to local conditions as users tracked their own progress. Nevertheless, it can be said that Fearnside (1986, xiii) has contributed greatly to, as he says, “developing a sorely needed area of ecological research: an adequate science of carrying capacity”.

Recommended responses to CCA challenges

The only methodologies likely to be able to cope with complex CCA planning requirements are whole-system, fine-grain, dynamic models that accommodate a wide range of natural constraints. Of the authors studied, Fearnside offers by far the most comprehensive approach although some elements of Fairlie's methodology are also worthy of consideration. A criterion-based summation helps to assess the existing challenges to CCA modelling and suggest ways forward.

Integrated systems

Most existing CCA methodologies contain the underlying assumption of a business-as-usual approach to the production and consumption of resources. As such, a global market economy incorporating fossil-fuel-based conventional farming methods is assumed to have the ability to continue producing the resources necessary for the maintenance of current lifestyle patterns. However, this assumption neglects to take into consideration that current global production and consumption, based on the competitive market growth imperative, are not only resource exploitative and inequitable but ultimately unsustainable. An unsustainable system, by definition, is one that cannot and will not last. So, perhaps the application of CCA to current conventional systems of resource production may be viewed primarily as a short-term or instructive measure. A more long-term approach to CCA would be to test possible future scenarios as a whole-of-system re-design including reviews of political and economic structures, land-ownership considerations and enterprise opportunities to name but a few. Some initial steps in this direction have been made by Fairlie (2007) in his comparisons of conventional farming to permacultural and organic production. He also uses the process of discerning land-use, resource-use, and diet to develop workable combinations that maximise carrying capacities. Alternatively, Fearnside integrates economic factors and highlights problems within financial systems. A key methodological challenge identified by this research involves the integration of complex whole systems into future CCA models.

An ideal CCA model should offer choices in underlying systems. Each system should run as a separate simulation. This system-modelling process should achieve certain benchmarks. Firstly, users should be directed to develop sustainable combinations of integrated elements. For example, prompts might include: what form of land ownership would facilitate this lifestyle arrangement? What scale of land-use best suits this system? How are resources best shared in this system? Secondly, the modelling should determine a range of possible means-of-production systems for the population addressing essential resources such as food, shelter, clothing and fuel. Lastly, users should determine appropriate land requirements for societal functions. For example, estimates should incorporate housing (at various densities and configurations), community facilities and transport infrastructure. Demographic and economic imperatives should also be considered. For instance, what are optimal population sizes to effectively deliver social service diversity such as medical facilities?

An all-encompassing systemic response is likely to be difficult to achieve given the breadth and complexity of the subject matter. Initially, the range of relevant systems should be catalogued, then possible implications of each should be examined. Even if a computer model is not able to accommodate all potential systemic parameters, it should at least prompt users to consider all options.

Cultural habits

Diet is viewed as a key determinant of societal choices affecting carrying capacity because it dictates a population's land requirements. A CCA model should examine existing diet to determine food items required. Items should be listed in their most basic form (e.g. carrots, tomatoes, potatoes). It should determine caloric and protein content of each food item and also determine minimum and optimal caloric and protein requirements of the population. Then, the population should be matched with production rates and land requirements (on a food by food basis). Lastly, food items should be ranked as essential and optional. Current modern diets often contain a variety of speciality items that may or may not be able to be produced locally. Data needs to be compiled on a wide range of foods concerning calories, protein, production rates and land requirements.

Dynamic timeframes

As per Fearnside's approach, CCA modelling should be viewed as a continuing process rather than a single event. Users should continuously and iteratively aim to better maximise social and environmental outcomes. Consequently, an ideal model should begin with some basic assumptions based on pre-existing conditions but once CCA commences, users should then be prompted to enter more detailed data on an ongoing basis concerning, for example, crop yield and environmental quality indicators (e.g. erosion, fertility, biodiversity). The model should also make projections over various timeframes and provide for public transparency of information to enable individuals to see the impact of their choices. Lastly, the model should allow for interaction and feedback between various elements and accommodate random variation in possible outcomes. The gathering of data affecting all elements of CCA is crucial to the accuracy of any simulations. This needs to occur both before any initial modelling begins as well as during the course of implementation.

Impacts and risk
Fearnside was the only author in this study whose model allowed the user to dictate acceptable levels of risk. Based on his analysis of past events, he was able to assess thresholds at which failure was likely to occur. In this instance, failure for Fearnside's colonists was not life threatening because presumably, they just returned to their previous homelands if crops failed or finances ran out. However, failure to meet carrying capacity constraints in a future resource-constrained world may lead to dire consequences when there is nowhere else for people to go.

Fearnside's approach to risk management offers excellent methodological possibilities. However, it seems likely that in some instances, only estimated predictions of systemic failure thresholds will be available for incorporation into any model rather than historic data. Determinants of impact and failure need to be further refined such as thresholds of failure related to calorie and protein production, environmental degradation, climate variability, soil productivity and social function.

Constraints
As Cohen (1995, p.220) explains, “If the interactions among potential constraints were well enough understood to be modelled reliably, system models would be attractive for conditional estimates of how many people the Earth can support in various modes of life.” It is important not only to map all constraints but to also identify the most crucial. For Fairlie, the production of food is viewed as the most limiting factor of carrying capacity. According to Skinner (1969, p.154), “more than any other factor, availability of water determines the ultimate population capacity of a geographic province.” Fearnside found that animal protein is one of the most important constraints and Summers only considers demographic and cadastral limitations.

Natural and social constraints applicable to the area of land under question should be mapped as thoroughly as possible. Users should have the ability to adjust the variables (e.g. rainfall, fertility, amount of fossil-fuel available, acceptable distances of travel between social functions) and return appropriately adjusted results. Several aspects require consideration: mathematical formulas need to be developed to track relationships between constraints with a hierarchy of constraints dictating the highest priority concerns and data needs to be gathered on the nature of each constraint (how it relates to other elements within the systems at a macro- and micro-level).

Suggest alternatives
From the outset, the CCA model should offer suggestions to the user on how the proposed area of land might be best utilised. For instance, users could be prompted on various aspects of diet, such as the proportion of red meat, to ascertain how human choices affect eventual carrying capacities. The model should also direct the user to continually strive to improve their carrying capacity by refining the design and adjusting lifestyles. By highlighting the weaknesses in any potential design, the model itself might highlight the areas for priority planning. Modelling questions include: how is it possible to detect contradictory conditions? How can users be prompted to make informed choices? How are design weaknesses identified?

Credible data
As Fearnside (1986, p.78) explains, “the potential importance of carrying capacity in formulating sustainable population and development policies points to the need for much more effort, both in

theoretical development and in data collection." Data needs to be gathered which is specific to the studied population (where possible). Types of data include lifestyles (choices in diet, clothing, transport, housing, effects of certain technology, production systems, population configurations and trade), land (measure areas, determine existing land uses), resources (inventory of existing resources and determination of resources required) and environment (impact determinants and assimilation factors).

Usability

Graphic presentation of relevant data is an essential element in any workable CCA modelling system. Graphs, diagrams, visualisations and 3D representations would all be potentially informative. The interface would also need to allow easy input of data and the underlying methodology should also be transparent enough for users to have confidence in the results. Existing systems-simulation software needs to be assessed to gauge possible applicability to CCA. For example, Haraldsson and Olafsdottir (2006) used Powersim2.5 for their analysis of Iceland's pre-industrial carrying capacity. Alternatively, new software may need to be developed.

Future planning

Fearnside, in particular, identified land-use planning as one of the prime reasons for undertaking CCA. However, few planners have taken up this challenge. Likely changes in future lifestyle patterns underlined by existing global inequality and initiated by global trends and natural constraints, gives renewed importance to the carrying capacity imperative. It is envisaged that sustainable design outcomes may be optimised by addressing land-use and community planning imperatives simultaneously, and by filtering this decision-making process through a flexible CCA model. Possible planning applications include: determination of population distribution and caps to assist long range infrastructure planning (e.g. roads, bridges, services); development of future planning scenario options for community education, deliberation and choice; the redistribution of populations to fit carrying capacity capabilities; the design and layout of communities that optimise resource usage; adjustment of lifestyle patterns to align with carrying capacity constraints; and implications of an integrated systems approach encompassing economic-environmental accounting, educational imperative and political processes.

One of our greatest current challenges is to transform the idea of CCA into sustainable land-use practice. However, if tools are developed to more easily deal with the complex nature of this topic, it is hoped that societal acceptance of, and commitment to, the carrying capacity imperative may grow.

Fine-grain scale

In order to arrive at any carrying capacity assessment, a land area to which the calculation applies must first be defined. According to Cohen (1995, p.128), the system-modelling of populations is best approached, "on a small geographic scale." While Summers and Fearnside achieve a reasonable degree of small-scale delineation, both chose socially dictated rather than geologically defined boundaries. The problem with their approach is that existing lot boundaries are too often susceptible to alteration, thus complicating long-term analysis. Consequently, topographically defined, rather than politically dictated boundaries best define the population carrying capacity for any given area. In aiming for a high degree of local self-reliance in basic, frequent-use and bulk item needs (Mochelle, 2006b, p.13), the designated community boundary should encompass the production and consumption of most resource requirements; capture the environmental assimilation of wastes; allow a safety margin for seasonal and climate variability, possible resource interruptions, exports, imports and visitor influxes; and include land set aside for natural habitat within the defined precinct to facilitate biodiversity and ecosystem services. Given that these aspects will generate a wide variety of possible design outcomes dependant on each specific locale, an ideal CCA should incorporate a degree of scalability from regional to local to micro-local.

Mochelle (2006b) proposes aligning regional boundaries and establishing local precincts or planning cells on the basis of water sub-catchments or tributary basins. This process would involve identifying and mapping all ridge-lines and water-ways and then considering an appropriate scale of delineation. Choices for scale might be determined by several factors. Firstly, available transportation should be considered. For instance, are there options for public transport, bicycles and private vehicles or is walking the most common transport? Social function and equitable access should also be assessed. For instance, is there sufficient internal enterprise for a wide range of human abilities and interests? What are optimal population sizes to effectively deliver social service diversity such as medical facilities? Lastly, resource usage should be considered. For instance, how much land is required for localised production and assimilation of most resources including water capture and storage? (Mochelle, 2006b, p.15).

Natural habitat

In order to maintain long-term sustainable human settlement patterns, natural environments will need to be nurtured and protected. CCA models can play an important role in encouraging people to realise that human systems are dependant on the physical limits of natural ecosystems and they can also help to educate and inform local communities of the vital role that natural environments play in sustaining human life. They should prompt lifestyles that enhance and protect natural ecosystems and offer guidelines for the identification, delineation and protection of highest priority areas. CCA modelling, in isolation, might not provide sufficient education in ecosystem preservation to ensure universal compliance. Further education initiatives would also need to be enacted.

Feasibility

Livi-Bacci (1989, p.224) argues that, “the identification of carrying capacity presents so many conceptual difficulties as to be virtually useless for practical purposes”. If the only aim of CCA analysis is to prescribe an exact maximum population figure then Livi-Bacci is correct, the practical purposes are not only limiting but virtually impossible. Nevertheless, there have emerged several workable examples of CCA models. Fearnside's achievements alone suggest that it is possible to create a model that, while not definitive, provides valuable insight into complex systems. The feasibility of developing such a model as an accessible tool for future land-use planners is challenging given that Fearnside took aver a decade to record and correlate his data. However, it is envisaged that incorporating both flexibility and expandability into the model might reduce this timeframe considerably. As such, land-use planners could begin the process with some pre-determined base-line indicators and refine their estimate of regional carrying capacity over time as more data is gathered and conditions change. Introducing a computerised process might also offer time-saving potential in the processing of large amounts of data.

It is thus envisaged that it might be possible to develop a computerised CCA model that estimates potential population and environmental limits. An array of interconnected data comprising various consumption choices, resource production systems, environmental assimilation mechanisms and natural constraint parameters, would need to be initially built into the model. A user would then be prompted to include various parameters pertinent to a particular site and/or population such as food production systems, dietary choices, land area, rainfall, soil fertility, resources required and percentage of land dedicated to nature reserve. Basic information entered into the model would generate a generalised carrying capacity range, while more detailed ongoing data would refine this output.

Conclusion

In recent decades, a fossil-fuel-based globalised system of trade has made the study of population carrying capacity seem largely irrelevant because humanity's wants and needs have not been tied to any singular locale. We have enjoyed summer fruits during winter, resources sufficient to support massive population centres and enough inexpensive energy to shift vast quantities of goods to anywhere on the globe. Our level of consumption has been driven more by consumer desire than any physical environmental constraints. However, as Blaxter (1986, p.91) points out, even though "the carrying capacity of the world cannot be expressed with any certainty… what is certain is that there are limits." It is becoming increasingly obvious that we are now approaching the earth's natural limits, and in the future, lifestyles will inevitably need to align more closely with local environmental conditions.

Carrying capacity assessment is a vital tool by which to measure the inherent local and regional productive limits for a given area of land. It provides a method of defining sustainable boundaries for future land-use planning and directly links a local community to their landscape. From a spatial planning perspective, CCA informs not only the size of any development but also the systemic processes involved in its design. Ultimately, changes in land usage will not occur in a vacuum and any environmental imperatives will have concurrent implications for other societal institutions such as economics, governance and education. For instance, how will land-ownership systems need to change to meet new resource requirements? How will systems of justice help to deliver equitable outcomes? What educative mechanisms would need to be enacted?

It is clear that our current usage of resources, our land planning practices, indeed our entire modern lifestyle, is inequitable, profligate and unsustainable. Piecemeal attempts to combat this predicament are unlikely to succeed if they do not address systemic failings and do not accurately and unequivocally hold populations accountable to their immediate environment. Given existing global population pressures, we can no longer afford to ignore the imperative, nor its implications. As Fearnside (1986, p.157) implores, "the time has come to take practical steps to avoid the human suffering that comes from exceeding carrying capacity". Fortunately, credible methodological approaches for carrying capacity assessment have been developed in recent decades. These urgently need to be further improved, refined and placed in the hands of planners, designers and communities, to steer infrastructure and land-use planning onto a path of genuine sustainability.

References

Barbier and Scoones, 1993 E. Barbier and I. Scoones, Economics and Ecology, Chapman and Hall, London (1993).

Beder, 2006 S. Beder, Environmental Principles And Policies, UNSW Press, Sydney (2006).

Bicknell et al., 1998 K. Bicknell, R. Ball, R. Cullen and H. Bigsby, New methodology for the ecological footprint with an application to the New Zealand, Ecological Economics 27 (1998), pp. 149–160. Article | PDF (93 K) | View Record in Scopus | Cited By in Scopus (114)

Blaxter, 1986 K. Blaxter, People, Food and Resources, Cambridge University Press, New York (1986).

Cohen, 1995 J.E. Cohen, How Many People Can The Earth Support?, W.W. Norton, New York (1995).

Cole and Sinclair, 2002 V. Cole and J. Sinclair, Measuring the ecological footprint of a Himalayan Center, Mountain Research and Development 22 (2002), pp. 132–141. Full Text via CrossRef | View Record in Scopus | Cited By in Scopus (18)

Fairlie, 2007 S. Fairlie, Can Britain feed itself?, The Land 4 (2007), pp. 18–26.

Fearnside, 1986 P. Fearnside, Human Carrying Capacity of the Brazilian Rainforest, Columbia University Press, New York (1986).

Graymore, 2005 M. Graymore, Journey to Sustainability: Sustainable Carrying Capacity and Sustainability Assessment Methods, Faculty of Env. Science, Griffith University, Brisbane (2005).

Graymore et al., 2009 M.L.M. Graymore, N.G. Sipe and R.E. Rickson, Sustaining human carrying capacity: a tool for regional sustainability assessment, Ecological Economics 69 (3) (2009), pp. 459–468.

Gutteridge, 2006 M. Gutteridge, How Big Is The Pond? South East Queensland's Ecological Footprint & Carrying Capacity, Department of Natural Resources and Mines, Queensland Government, Brisbane, Qld (2006).

Haraldsson and Olafsdottir, 2006 H.V. Haraldsson and R. Olafsdottir, A novel modelling approach for evaluating the preindustrial natural carrying capacity of human population in Iceland, Science of the Total Environment 372 (2006), pp. 109–119. Article | PDF (948 K) | View Record in Scopus | Cited By in Scopus (3)

Livi-Bacci, 1989 M. Livi-Bacci, A Concise History of World Population, Blackwell, Oxford (1989).

McConnell, 1995 R. McConnell, The human population carrying capacity of the Chesapeake Bay watershed: a preliminary analysis, Population and Environment 16 (1995), pp. 335–351. Full Text via CrossRef | View Record in Scopus | Cited By in Scopus (9)

Meadows et al., 1972 D. Meadows, D. Meadows, J. Randers and W. Behrens, The Limits Of Growth. A Report for the Club of Rome's Project on the Predicament of Mankind, Pan, London (1972).

Mochelle, 2006a Mochelle, R., 2006a. Agricultural Carrying Capacity and Footprint Calculation Data: Australia. Unpublished working document, sourced from author at QUT, GPO Box 2434, Brisbane QLD 4000.

Mochelle, 2006b Mochelle, R., 2006b. Conceiving the Rural Precinct and Its Boundaries: Towards A New Framework for Rural Planning, Unpublished. Dept Nat Resources & Mines, Qld Gov, State Government of Queensland, GPO Box 2454, Brisbane Qld 4001.

Mwalyosi, 1991 R. Mwalyosi, Population growth, carrying capacity and sustainable development in South-West Masailand, Journal of Environmental Management 33 (1991), pp. 175–187. Abstract | View Record in Scopus | Cited By in Scopus (4)

Parker and Selman, 1997 J. Parker and P. Selman, Working towards sustainable communities in Canada, The London Journal of Canadian Studies 13 (1997), pp. 61–76.

Pimentel and Pimentel, 2004 D. Pimentel and M. Pimentel, World Population and Food Problem, Cornell University, Ithaca, NY (2004).

Skinner, 1969 B. Skinner, Earth Resources, Prentice-Hall, Englewood Cliffs, NJ (1969).

Summers, 2004 P. Summers, Population Carrying Capacity in Noosa Shire, Noosa Council, Tewantin (2004).

Vail, 2006 J. Vail, Envisioning a Hamlet Economy: Topology of Sustainability and Fulfilled Ontogeny (2006) http://www.jeffvail.net/2006/04/envisioning-hamlet-economy-topology-of.html.

Van Den Bergh, 1993 J. Van Den Bergh, A framework for modelling economy-environment-development relationships based on dynamic carrying capacity and sustainable development feedback, Environmental and Resource Economics 3 (1993), pp. 395–412. View Record in Scopus | Cited By in Scopus (10)

Wackernagel and Rees, 1996 M. Wackernagel and W. Rees, Our Ecological Footprint: Reducing Human Impact on Earth, New Society Publishers, Gabriola Island, BC (1996).

Wetzel and Wetzel, 1995 K. Wetzel and J. Wetzel, Sizing the Earth: recognition of economic carrying capacity, Ecological Economics 12 (1995), pp. 12–21.