

# **THE CARRYING CAPACITY IMPERATIVE: ASSESSING REGIONAL CARRYING CAPACITY METHODOLOGIES FOR SUSTAINABLE LAND-USE PLANNING**

**Murray Lane**

172 / 251 Varsity Pde, Varsity Lakes Q 4227, Australia, lanemc@qut.edu.au

## **ABSTRACT**

The global impact of an ever-increasing population-base combined with dangerously depleted natural resources highlights the urgent need for changes in human lifestyles and land-use patterns. To achieve more equitable and sustainable land use, it is imperative that populations live within the carrying capacity of their natural assets in a manner more accountable to and ethically responsible for the land which sustains them. Our society's very survival may well depend on worldwide acceptance of the carrying capacity imperative as a principle of personal, political, economic, educational and planning responsibility. This theoretically-focussed research identifies, examines and compares a range of methodological approaches to carrying capacity assessment and considers their relevance to future spatial planning. It also addresses existing gaps in current methodologies and suggests avenues for improvement. A set of eleven key criteria are employed to compare various existing carrying capacity assessment models. These criteria include whole-systems analysis, dynamic responses, levels of impact and risk, systemic constraints, applicability to future planning and the consideration of regional and local boundary delineation. This research finds that while some existing methodologies offer significant insights into the assessment of population carrying capacities, a comprehensive model is yet to be developed. However, it is suggested that by combining successful components from various authors, and collecting a range of interconnected data, a practical and workable systems-based model may be achievable in the future.

Keywords: carrying capacity methodologies, population limits, resource depletion, sustainable land-use, spatial planning.

## **INTRODUCTION**

It is widely recognised that the global impact of an ever-increasing population-base, 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 (1798, 1960) 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

## The Carrying Capacity Imperative

of comfort, and Malthusian sceptics (Cohen 1995, 37) argue that his predictions of over-population have not eventuated because advanced technology and the use of high-energy fossil fuels have allowed for a significantly expanded resource-base. However, this mode of industrialised production and consumption has proven costly, with social dislocation, economic inequities and environmental degradation becoming global problems (Sandler, 1997, xiii).

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, 1). Peak oil has particular relevance to this issue with the Queensland Government's report on its vulnerability to rising fuel prices stating in 2007 that demand for oil, "will exceed supply, probably in the next 10 years" (McNamara, 2007, 8). This report and subsequent Action Plan suggests that, "the implications of peaking conventional oil production will also interact with a broad range of political, technical, environmental and social change drivers" (Waller, 2008, 10).

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 land-use patterns, human ecologist Garrett Hardin (1986) recommends directly linking and limiting 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 in perpetuity in an area... without causing environmental degradation" (Fearnside, 1986, 73). 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 consider 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?

## The Carrying Capacity Imperative

This study suggests that the application of CCA on a regional scale could underpin the development of guidelines for future land-use planning, influence community decision making by highlighting issues of resource accountability and ultimately underpin the entire urban and rural design process. A growing awareness of the importance of this issue has already begun to infiltrate political rhetoric with Councillor Green, of the Sunshine Coast Regional Council arguing in his submission to the 2009 regional plan review that, “we need to have a thorough understanding of the carrying capacity of our region” (Hoffman, 2009) in order to develop appropriate infrastructure requirements. He concludes, “[t]hat includes consideration of the impacts of climate change, reducing our energy and water consumption and greenhouse gas emissions and recognising the need to manage the implications of peak oil.”

Sustainable lifestyle patterns need to be adopted that limit environmental degradation and also provide the resources necessary for human wellbeing. This would inevitably imply a whole-system 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.

### RESEARCH APPROACH: 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 local or regional implications. As such, methods for defining small-scale boundaries for CCA studies need to be considered. While several current models focus 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.

In assessing population modelling tools, Kelly (1988, 1686) argues they should incorporate potential feedback from direct and indirect societal impacts; they should accommodate institutional change in political, economic and demographic configurations and they need to have timescales extending, “over a period of at least one life cycle (around 60 years).” Cohen (1995, 359) describes the ideal CCA model as a balance between human choices and natural constraints. Most criteria for CCA assessment used in this research (listed below) are based on Cohen’s hypothetical ideal model.

#### **Assessment criteria against which existing methodologies can be judged:**

1. Allow for choice in underlying *whole systems*, including political and economic institutions, technology, demographic arrangements, environmental conditions, moral values, and levels of (and distribution of) societal well-being.
2. Allow for choice in *cultural habits* such as diet, fashion, taste and tradition.
3. Proffer *dynamic* responses allowing for various time-frames and random variation.

## The Carrying Capacity Imperative

4. Assess levels of *impact* and risk. “Users would specify the state of the world they wished to leave at the end of a specified period” (Cohen, 1995, 359).
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); and climatic systems (e.g. climate change, rainfall, seasonal variations).
6. Check for inconsistencies and suggest *alternatives* by prompting users to resolve problems or “specify a balance among contradictory choices” (Cohen, 1995, 359).
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.

The employment of such a comprehensive set of criteria to assess and compare CCA methodologies sets a challenging benchmark. The aim of this study is to explore the best CCA methodologies currently available and suggest how these might be combined and improved upon. This study attempts to come to grips with the theoretical manner in which this calculation can be best derived. The actual collection of data for CCA should form the basis of another study.

## CCA METHODOLOGIES – EXISTING RANGE

An assessment of current carrying capacity literature suggests that methodological approaches can be categorised into basic typologies. For example, Chisholm (1999, 20) cites two possible CCA methodologies, namely density comparisons and potential food production. While simplistic, these approaches certainly incorporate many existing methodologies, but would need broadening to incorporate the entire current range. Consequently, for this study, Chisholm’s density-based category has been expanded to include other societal dynamics such as population distribution, economic factors and demographic trends; and his food-based typology is expanded to include other environmental constraints such as additional resources and environmental impacts. Cohen (1995, 111) proposes a third CCA methodology, a systems model, which combines both societal and environmental parameters. He describes this methodological typology as a comparison of quantitative, “population growth and size with nondemographic factors such as industrialisation, agriculture, pollution and natural resources.”

### Societal CCA methodologies

CCA analyses based primarily on societal parameters are largely extensions of population models such as the United Nations World Population Prospects (2009). This publication merely gives a range of future population projections based on past trends and societal factors such as fertility, mortality, disease and migration. In some cases, population projections are extended to also include upper limits usually based on demographic considerations. While quite limited in their scope, these methodologies may be considered CCA models. Some local

## **The Carrying Capacity Imperative**

government jurisdictions, including the Douglas Shire (Banfield, 2000, 4) and Noosa Shire in 1996 and 2001 (Summers, 2004), have published optimal population projections. According to Banfield (2000, 4), these studies were undertaken primarily to, “counter the impacts of population growth and tourism pressures.”

A further societal-based approach involves linking population carrying capacity to economic limitations. Wetzel and Wetzel (1995, 13), for example, developed a model for economic carrying capacity which, “takes the form of maximum global economic welfare derived from the sustainable throughput flows of the ecosphere.” This hybridised societal-environmental typology, also adopted by Scoones (Barbier and Scoones, 1993, 96) for analysing pastoral systems in Zimbabwe, incorporates natural processes but ultimately calculates carrying capacity 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 environmental within which society exists. Consequently, this methodological approach is extremely narrow in scope.

### **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 current 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 their total land requirements. However, as Beder (2006, 25) points out, this land area is, “not necessarily all in the one place but may be spread all over the globe,” and according to Gutteridge, it assumes business-as-usual energy supplies and steady-state agricultural yields (2006, slide 8). Exponents of this approach include Cole and Sinclair (2002), Bicknell et al. (1998), and Parker et al (1997). Other authors who have developed their own methodology but concentrate more on environmental impacts than resource availability include Mwalyosi (1991), Graymore (2005, 262) 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, 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 (2007) study of Great Britain. 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.

### **Systems CCA methodologies**

Systems-based CCA methodologies not only examine a number of concurrent factors effecting population limits but also consider the relationships between these factors (Cohen, 1995, 111). 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, 13) argues that this seminal work, for the first time, highlights the incompatibility of population growth and resource availability, according to Fearnside (1986, 73), it focuses on instantaneous rather than sustainable CCA methodologies. Fearnside, developed his own sustainable CCA model which examines interconnected relationships in resource usage over extended

## The Carrying Capacity Imperative

time-frames. 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 (2006).

### COMPARATIVE ANALYSIS OF THREE CCA METHODOLOGIES

Three CCA models have been selected for detailed analysis, each illustrating a different methodological approach and a different geographic scale: 1. Paul Summers: “Population Carrying Capacity in Noosa Shire” (2004) – societal methodology at a regional scale. 2. Simon Fairlie: “Can Britain Feed Itself?” (2007) – environmental methodology at a national scale. 3. Philip Fearnside: “Human carrying capacity of the Brazilian rainforest” (1986) – systems methodology at a local scale.

#### **Societal methodology: Paul Summers, “Population Carrying Capacity in Noosa Shire”**

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, 4).

##### *1. Whole systems*

Only existing cadastral and demographic systems are included in this analysis. Implied assumptions of continued existing lifestyle patterns are also imbedded.

##### *2. Cultural Habits*

No references are made to user choices.

##### *3. Dynamic timeframes*

Retrospective analysis (in comparing 2001 census figures with those of 1996) is more obvious than future projections. While Summers (2004, 3) explains that the study is not an analysis of growth rates, he does make one forward projection that carrying capacity would be reached by 2009. However, it is not clear how this was determined.

##### *4. Impacts and risk*

There is no scope for assessing potential impacts, only a calculation of probable population numbers. Summers’ bibliography lists no environmental and resource-based literature.

##### *5. Constraints*

The only implicit constraints considered are spatially and demographically orientated (development guidelines and population trends). Summers makes reference to “biophysical constraints to further subdivisions” without describing any such constraints, nor outlining how they were employed (2004, 17). Similar studies conducted by the Douglas Shire also include minimal resource constraints, referring only generally to the protection of nature reserves and prime agricultural land (Banfield, 2000, 2).

##### *6. Suggest alternatives*

No systemic inconsistencies are mentioned and no alternative suggestions undertaken.

## The Carrying Capacity Imperative

### *7. Credible data*

The modelled data (census results and planning documents) is from reputable sources. However, given that the parameters of data entered into the model are narrowly focussed, the resultant carrying capacity conclusions are equally limited.

### *8. Usability*

While the data is well laid out and calculations reasonably understandable, there is no scope in Summers' study for user interactivity.

### *9. Future planning*

Summers (2004, 24) states that his, "capacity figures should be used to gauge both the needs of the community for the future and importantly, the ability to cater for those needs." He suggests that the study could be used in estimates of the size and timing of services and infrastructure requirements for residents and visitors relating to water supply, sewerage, roads, parking and community facilities (Summers, 2004, 24).

### *10. Fine-grain scale*

Based on existing lot boundaries, Summers breaks the district into 82 smaller spatial Collections Districts (CDs) of up to about 5000 people. 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. However, Mochelle (2006b, 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. For instance, there are already anomalies between Summers' 1996 and 2001 (2004, 3) studies due to adjustments in CD alignments and this problem might be further compounded in any future similar studies given the amalgamation of the Noosa Shire into the Sunshine Coast Regional Council in 2008.

### *11. Natural Habitat*

Summers (2004, 23) acknowledges that population growth can not continue unchecked, "without a decline in the quality of the environment." However, his CCA model neglects to include environmental parameters, concentrating merely on societal demographic concerns.

### *Conclusions*

Summers' study takes an important step in beginning to link local government planning guidelines and infrastructure commitments to societal and environmental limits. It succeeds in its legibility, the reliability of its data and the approach of small-scale analysis. However, the limitations of this study stem from 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 methodology: Simon Fairlie – "Can Britain Feed Itself?"**

Simon Fairlie's (2007, 18) approach to carrying capacity begins with a simple question, "Can Britain feed itself?" While the question is a reasonably narrow one, the processes involved in divining an answer are methodologically illuminating. Fairlie proposes six separate agricultural approaches by which to test this hypothesis and the answer in each case is in the affirmative - according to Fairlie, Britain is able to produce the food necessary to feed its current population.

## The Carrying Capacity Imperative

### *1. Whole systems*

While Fairlie's approach falls short of addressing all relevant system considerations required for reliable CCA, he does begin to approach various aspects of the problem at its 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, 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, 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.

### *2. Cultural habits*

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.

### *3. Dynamic time-frames*

Dynamic, real-time analysis is not present in this study, but Fairlie (2007, 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,



## The Carrying Capacity Imperative

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.

### *4. Impacts and risk*

Brief details describing implications of the permacultural approach are given but these lack detail and do not include any risk analysis.

### *5. Constraints*

This 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, 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 don't figure directly in the CCA calculations.

### *6. Suggest alternatives*

Alternate systemic choices extend only as far as chemical, organic and permaculture options.

### *7. Credible data*

Fairlie (2007, 26) draws his data from seemingly credible statistical sources such as industry groups (Organic Farm Management Handbook, 2007) and government (Annual Abstract of Statistics and Agriculture in the UK, 2006).

### *8. Usability*

Fairlie's analysis is presented as a journalistic paper rather than a usable model, but the methodology is relatively clearly described and theoretically could be applied to other populations and locations.

### *9. Future planning*

Fairlie (2007, 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.

### *10. Fine-grained scale*

Based on a broad-brush analysis, this study takes little account of localised conditions.

### *11. Natural habitat*

While this CCA is an environmental-based model, consideration of natural systems is limited to a reasonably anthropocentric viewpoint. Rather than accommodating the diverse needs of natural habitats and wildlife areas, Fairlie focuses primarily on land and system requirements for human use.

### *Conclusions*

In developing an environmentally-orientated CCA model, Fairlie, together with Gutteridge, concentrates more on resource availability than on environmental impacts. This is the inverse

## The Carrying Capacity Imperative

of most ecological footprint analyses based on the work of Rees and Wackernagel (1996). Fairlie (2007, 18) states that the aim of this study is to ascertain land-use requirements in non-conventional agriculture given that, “the UK may have to become a lot more self reliant than it is now.” 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.”

### **Systems methodology: Philip Fearnside – “Human carrying capacity of the Brazilian rainforest”**

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.

#### *1. Whole systems*

Fearnside’s (1986, 148) model for CCA begins to address the topic of whole-system integration. He writes, “to be viable, an agroecosystem must ensure minimum living standards.” As such, potentially his model informs, and is informed by, users’ lifestyle decisions in various following ways. Firstly, Fearnside (1986, 116) incorporates demographic variables such as geographic distribution, age structure, rate of growth, and absolute size. However, 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, 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, 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.”

#### *2. Cultural habits*

Fearnside uses the local diet to help define the population’s lifestyle. He found that 70% of each household’s food supply was home-grown from limited foodstuffs. Fearnside (1986, 114) extrapolates this diet into both calories and protein components. Then, in ascertaining a benchmark for average nutritional intake, he compares actual consumption amounts with theoretical subsistence levels and also with Brazilian government recommended quantities.

#### *3. Dynamic time-frames*

Fearnside (1986, 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, 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.”

#### *4. Impacts and risk*

Fearnside’s approach can be described as a threshold-based, risk assessment employing multiple limiting factors including environmental degradation (e.g. proportion of land cleared

## The Carrying Capacity Imperative

and soil fertility) and individual consumption (e.g. caloric and protein intake and cash requirements). Fearnside's (1986, 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, 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, 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."

### 5. Constraints

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 the following: 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, 123).

### 6. Suggest alternatives

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, 87), is the ability to learn from feedback, iteration and testing alternative scenarios which otherwise might be "impossible or impractical to test directly using the real-world system." 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, 92). As such, feedback occurs both within the simulation and between the simulation and the real world. It is unclear how any clashes in contradictory feedback might be treated within Fearnside's system, but there is at least mention made to the difficulty of resolving dilemmas such as Garret Hardin's (1977) "Tragedy of the Commons" where individual gain is obtained to the detriment of shared resources (Fearnside 1986, 150).

### 7. Credible data

This is a focused study of one settlement area extending about 15km wide and 30km 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.

### 8. Usability

Fearnside's model 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

## The Carrying Capacity Imperative

in the detail. Some of the resultant modelling also seems to deviate from expectations but Fearnside (1986, 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.

### *9. Future planning*

From the outset, Fearnside (1986, 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, 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 Fearnside’s (1986, 115) study generated 71% of their own caloric food intake and 95% of their own protein.

### *10. Fine-grained scale*

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, 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, 155) admitting that, “land tenure patterns are inseparable from carrying capacity.”

### *11. Natural habitat*

Fearnside (1986, 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, 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.

### *Conclusions*

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.”

## The Carrying Capacity Imperative

### RECOMMENDED CRITERION-BASED 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.

#### 1. Whole systems

##### *Challenges:*

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 can not 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. How can this be best achieved?

##### *Recommended Response:*

An ideal CCA model should offer choices in underlying systems. Each system should run as a separate simulation. This systems 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?

##### *Gaps:*

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.

## The Carrying Capacity Imperative

### 2. Cultural habits

#### *Challenges:*

Fairlie, Gutteridge, Mochelle and Fearnside analysed the local diet of the population they were studying to determine their basic needs. They used an analysis of diet choices, consumption rates, and calorie requirements to ascertain minimum land areas. How can cultural traits, particularly changes in diet and dietary habits, be most reliably and flexibly built into the modelling?

#### *Recommended Response:*

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.

#### *Gaps:*

Data needs to be compiled on a wide range of foods concerning calories, protein, production rates and land requirements.

### 3. Dynamic timeframes

#### *Challenges:*

Ideal CCA analysis is a dynamic process that measures the impacts of certain lifestyles and then influences the adoption or rejection of behaviours within people's lifestyles. How are long-term implications, real-time simulations and random variation best incorporated?

#### *Recommended response:*

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 time frames 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.

#### *Gaps:*

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.

## The Carrying Capacity Imperative

### 4. Impacts and risk

#### *Challenges:*

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. So, given that risks of systemic failure are best avoided, is it possible to replicate Fearnside's approach?

#### *Recommended response:*

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.

#### *Gaps:*

Determinants of impact and failure need to be further refined. For example, what are the thresholds of failure related to calorie and protein production, environmental degradation, soil productivity and social function?

### 5. Constraints

#### *Challenges:*

As Cohen (1995, 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, 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. Summers only considers demographic and cadastral limitations, but what about soil fertility, water and nutrient availability, logistical accessibility, and climate?

#### *Recommended response:*

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.

#### *Gaps:*

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).

### 6. Suggest alternatives

#### *Challenges:*

How can the model itself, prompt corrective action?

## The Carrying Capacity Imperative

### *Recommended response:*

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.

### *Gaps:*

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?

## 7. Credible data

### *Challenges:*

As Fearnside (1986, 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.”

### *Recommended response:*

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, trade), land (measure areas, determine existing land uses), resources (inventory of existing resources, determination of resources required), environment (impact determinants, assimilation factors).

### *Gaps:*

There is much data to be gathered before any CCA model can be accurately implemented.

## 8. Usability

### *Challenges:*

How can models be developed for people to utilise with minimal training?

### *Recommended response:*

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 a transparent enough for users to have confidence in the results.

### *Gaps:*

Existing systems-simulation software needs to be assessed to gauge possible applicability to CCA. For example, Haraldsson (2006) used Powersim2.5 for their analysis of Iceland’s pre-industrial carrying capacity. Alternatively, new software may need to be developed.

## 9. Future planning

### *Challenges:*

Fearnside, in particular, identified land-use planning as one of the prime reasons for undertaking CCA. However, few planners have taken up this challenge. How can carrying capacity analysis be made more relevant for land-use planners? What might be its future applications?



## The Carrying Capacity Imperative

### *Recommended response:*

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 whole-systems approach – economic-environmental accounting, educational imperative, political processes.

### *Gaps:*

One of the widest gaps in current thinking is merely a lack of awareness of the importance of CCA analysis in land-use planning. 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.

## **10. Fine-grain scale**

### *Challenges:*

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, 128), the systems-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. So, how are these small-scale land boundaries best determined?

### *Recommended response:*

Establish topographically defined, rather than politically dictated, fine-grained boundaries within which the population carrying capacity can be calculated. In aiming for a high degree of local self-reliance in basic, frequent-use and bulk item needs (Mochelle, 2006b, 13), the designated community boundary should: encompass the production and consumption of most resource needs; capture the environmental assimilation of wastes; allow a safety margin for seasonal 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 (as per following section on Natural Habitat).

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

## The Carrying Capacity Imperative

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, 15)

### *Gaps:*

Considerable data needs to be collected on all the above points.

## **11. Natural habitat**

### *Challenges:*

In order to maintain long-term sustainable human settlement patterns, natural environments will need to be nurtured and protected. How can CCA models encourage people to realise that human systems are dependant on the physical limits of natural ecosystems?

### *Recommended response:*

Ensure sufficient biodiversity of indigenous flora and fauna adjacent to human settlement by provision of natural habitat restoration. CCA models can 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.

### *Gaps:*

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, 224) argued in the 1980s that, “the identification of carrying capacity presents so many conceptual difficulties as to be virtually useless for practical purposes.” Since then, there have emerged several workable examples of CCA models. Fearnside’s achievements alone suggest that it is possible to create a model sophisticated enough to provide valuable insight into complex systems. 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. However, with the aim of providing a flexible tool for future land-use planning, then the creation of practical models indeed seems achievable. It is 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 entered into the computer model. Once the model is established, the user would 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.

## **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,

## The Carrying Capacity Imperative

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 don’t address systemic failings and don’t 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, 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

- Banfield, K. (2000) *Recognising Ecological Obligations in Planning. Rapi Limits to Growth Forum*. Coffs Harbour, Institute for Sustainable Futures.
- Barbier, E. & Scoones, I. (1993) *Economics and Ecology*, London, Chapman And Hall.
- Beder, S. (2006) *Environmental Principles And Policies*, Sydney, Unsw Press.
- Bicknell, K., Ball, R., Cullen, R. & Bigsby, H. (1998) *New Methodology for the Ecological Footprint with an Application to the New Zealand*. *Ecological Economics*, 27, 149 - 160.
- Blaxter, K. (1986) *People, Food and Resources*, New York, Cambridge University Press.
- Chisholm, A. (1999) *Land, Resources and the Idea of Carrying Capacity*. *Business Council of Australia Papers*, 1, 19-26.
- Cohen, J. E. (1995) *How Many People Can The Earth Support?*, New York, W. W. Norton.
- Cole, V. & Sinclair, J. (2002) *Measuring the Ecological Footprint Of A Himalayan Center*. *Mountain Research and Development*, 22, 132-141.
- Fairlie, S. (2007) *Can Britain Feed Itself? The Land*, 4, 18-26.
- Fearnside, P. (1986) *Human Carrying Capacity Of The Brazilian Rainforest*, New York, Columbia University Press.
- Graymore, M. (2005) *Journey to Sustainability: Sustainable Carrying Capacity and Sustainability Assessment Methods*, Faculty of Env. Science. Brisbane, Griffith University.
- Gutteridge, M. (2006) *How Big Is The Pond? South East Queensland's Ecological Footprint & Carrying Capacity*. Presentation to Department of Natural Resources And Mines, State Government of Queensland. Brisbane.

## The Carrying Capacity Imperative

- Haraldsson, H. V. & Olafsdottir, R. (2006) A Novel Modelling Approach For Evaluating The Preindustrial Natural Carrying Capacity of Human Population in Iceland. *Science of the Total Environment*, 372, 109-119.
- Hardin, G. (1986) Cultural Carrying Capacity. AIBS Annual Meeting. University of Massachusetts, Amherst.
- Hardin, G. & Baden, J. (1977) *Managing the Commons*, San Francisco, W. H. Freeman.
- Hoffman, B. (2009) Council Set To Fight Growth Push. *Sunshine Coast Daily Online Ed.* Maroochydore.
- Kelly, A. (1988) Economic Consequences of Population Change in the Third World. *Journal Of Economic Literature*, 26, 1685-1728.
- Livi-Bacci, M. (1989) *A Concise History Of World Population*, Oxford, Blackwell.
- Malthus, T. (1798, 1960) *An Essay on the Principle Of Population, as it Affects the Future Improvements of Society*, New York, Modern Library.
- Mcconnell, R. (1995) The Human Population Carrying Capacity of the Chesapeake Bay Watershed: A Preliminary Analysis. *Population and Environment*, 16, 335-351.
- Mcnamara, A. (2007) Queensland's Vulnerability to Rising Oil Prices Taskforce Report. Brisbane, Queensland Government.
- Meadows, D., Meadows, D., Randers, J. & Behrens, W. (1972) *The Limits Of Growth. A Report for the Club of Rome's Project on the Predicament of Mankind*, London, Pan.
- Mochelle, R. (2006a) Agricultural Carrying Capacity and Footprint Calculation Data: Australia. Unpublished Working Document, Sourced From Author.
- Mochelle, R. (2006b) *Conceiving the Rural Precinct and Its Boundaries: Towards A New Framework for Rural Planning*, Unpublished. Dept Nat Resources & Mines, Qld Gov.
- Mochelle, R. & Brisbin, C. (2008) *Rurban Systems Design - Carrying Capacity Calculation*. Brisbane, Qut.
- Mwalyosi, R. (1991) Population Growth, Carrying Capacity and Sustainable Development in South-West Masailand. *Journal of Environmental Management*, 33, 175-187.
- Parker, J. & Selman, P. (1997) Working Towards Sustainable Communities In Canada. *The London Journal of Canadian Studies*, 13, 61-76.
- Pimentel, D. & Pimentel, M. (2004) *World Population and Food Problem*. Ithaca, New York, Cornell University.
- Sandler, T. (1997) *Global Challenges: An Approach to Environmental, Political, And Economic Problems*, Cambridge, Cambridge University Press.
- Skinner (1969) *Earth Resources*, Englewood Cliffs, NJ, Prentice-Hall.
- Summers, P. (2004) *Population Carrying Capacity in Noosa Shire*. Tewantin, Noosa Council.
- United Nations (2009) *World Population Prospects. The 2008 Revision Highlights*. New York, Department of Economic and Social Affairs, Population Division.
- Vail, J. (2006) *Envisioning A Hamlet Economy: Topology of Sustainability and Fulfilled Ontogeny*
- Van Den Bergh, J. (1993) A Framework For Modelling Economy-Environment-Development Relationships Based on Dynamic Carrying Capacity And Sustainable Development Feedback. *Environmental & Resource Economics*, 3, 395-412.
- Wackernagel, M. & Rees, W. (1996) *Our Ecological Footprint: Reducing Human Impact on Earth*, Gabriola Island, BC, New Society Publishers.
- Waller, M. (2008) *Oil Vulnerability Strategy / Action Plan For Queensland: Research Paper* Brisbane, Heuris Partners Ltd.
- Wetzel, K. & Wetzel, J. (1995) Sizing the Earth: Recognition of Economic Carrying Capacity. *Ecological Economics*, 12, 12-21.