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The essential parameters of a resource-based carrying capacity assessment model: an Australian case study

Abstract

Carrying capacity assessments model a population's potential self-sufficiency. A crucial first step in the development of such modelling is to examine the basic resource-based parameters defining the population's production and consumption habits. These parameters include basic human needs such as food, water, shelter and energy together with climatic, environmental and behavioural characteristics. Each of these parameters imparts land-usage requirements in different ways and varied degrees so their incorporation into carrying capacity modelling also differs. Given that the availability and values of production parameters may differ between locations, no two carrying capacity models are likely to be exactly alike. However, the essential parameters themselves can remain consistent so one example, the Carrying Capacity Dashboard, is offered as a case study to highlight one way in which these parameters are utilised. While examples exist of findings made from carrying capacity assessment modelling, to date, guidelines for replication of such studies in other regions and scales have largely been overlooked. This paper addresses such shortcomings by describing a process for the inclusion and calibration of the most important resource-based parameters in a way that could be repeated elsewhere.

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Keywords

Carrying capacity; population; parameters; dynamic modelling; Dashboard; online interface

1. Introduction

Carrying capacity assessment, as a modelling tool for localised human resource self-sufficiency, has generally been overshadowed by its global variant, Ecological Footprint analysis. Given the globalised nature of modern trade, proponents of the Ecological Footprint approach argue that this analysis is a more accurate representation of existing circumstances (Wackernagel, 1994) where the geographic scale of consumption is variable while the global scale of production is usually fixed (Global Footprint Network, 2012). Recent community-led resurgence in the relevance of localised self-sufficiency (Holmgren, 2002; Peters et al., 2009; Hopkins, 2011) has seen some response from academia and government departments with recent studies including a report on the self-sufficiency of Hawaii County (Melrose and Delepart, 2012) and a comprehensive modelling of the agricultural carrying capacity of New York State (Peters et al., 2007). Adding to this renewed interest in carrying capacity modelling is the release of an online assessment tool for the Australian context, the Carrying Capacity Dashboard (http://dashboard.carryingcapacity.com.au/) (Lane, 2012).

The current global system of trade makes estimates of localised carrying capacity more complicated when production and/or consumption of any particular resource occur outside any localised boundary (Whyte and Beuret, 2004). Trade between different locations is actually an anathema to carrying capacity assessment at a theoretical level, given that carrying capacity estimates the productive potential of the landscape within a certain border at the exclusion of the land outside the border

(Fearnside, 1986). However, from a practical perspective, populations have historically been inclined to trade a certain amount of material goods with others as a way of sharing any internal surplus and making up for shortfalls (Cohen, 1995). As such, even though the focus of carrying capacity models is generally local, it is also important that they address the issue of trade by finding ways to incorporate the extent and impact of imports and exports between otherwise notionally self-sufficient regions.

Carrying capacity models are the primary vehicle for the estimation of a population's self-sufficiency. From a resource perspective, the most important parameters determining carrying capacity are basic human needs essential for a population's physical survival including food (Hopfenberg and Pimentel, 2001), water, shelter and energy. Each of these parameters imparts land-usage requirements in different ways so their incorporation into carrying capacity modelling also differs. Additionally, the integration of these parameters is dependent on data availability – a factor which may differ from one location to the next. Consequently, while the basic structure of resource-based carrying capacity models may remain consistent between studies, no two approaches are likely to be exactly alike. A case study approach to the question of optimum parameter integration is thus a useful way in which to highlight parameter integration as it provides a contextualised example of the essential concepts. This paper describes a process for the inclusion and calibration of the most important resource-based parameters in a way that could potentially be replicated by other researchers in other locations.

1.1 Why resource-based?

Carrying capacity parameters are determined by the constraints by which populations are limited. These constraints may potentially be biophysically orientated such as resource needs and environmental impacts, or can also be societally-focused (Lane, 2010). Viewed in isolation, the potential determinants of human carrying capacity could be analogous to Liebig's Law of the Minimum (Cohen, 1995). Liebig asserted that in agriculture, under steady-state conditions, a species' population size is constrained not by the total quantity of resources available, but by the scarcest resource. Relying solely on one factor is likely to offer only limited reliability as Liebig's Law does not adequately accommodate fluctuating environments, interactions amongst inputs, proportional relationships between populations and resources, and differing requirements of various populations (Cohen, 1995). Consequently, the determination of human carrying capacity necessitates the inclusion of an array of parameters (Fearnside, 1986). If all potential resources, impacts and societal constraints are to be incorporated into a carrying capacity model, the sheer size and complexity of the enterprise may render it beyond the scope of most projects. Consequently, a strategy for the prioritisation of some parameters over others is required.

One way by which to ascertain priority in the importance of carrying capacity modelling parameters is to ascribe them a chronological ordering. The pursuit of cultural endeavours described by Hardin (1986) is dependent on favourable biophysical conditions because without a healthy environment and adequate basic resources such as food and water, the inevitable poor-health of the population is likely to preclude such activity. Thus, it is possible to deduce that biophysical constraints have a higher chronological priority than societal aspirations. There are two forms of biophysical constraints: resource requirements and environmental impacts (Lane, 2010). The set of parameters related to resource requirements takes precedence over impacts because the degree of impact is often dictated by the amount of resources utilised. In a closed system (which carrying capacity assessment implies) there is a linear progression from resource production to resource usage (consumption) to resource assimilation (impacts and waste). Notwithstanding extreme environmentally destructive behaviour, the amount of resource assimilation is dictated by the amount of resources produced. The primary focus in this paper is placed on resource-based carrying capacity assessment modelling, with the majority of the parameters of Carrying Capacity Dashboard reflecting this bias.

2. Method

This paper will describe the parameters necessary for the development of Australian resource-based carrying capacity assessment tools by using the example of the Carrying Capacity Dashboard. Despite limiting the scope of this analysis to a resource-orientation, the breadth of potential parameters for subsequent modelling is still significant. To simplify a complex array of components, modelling for the Dashboard is categorised under five main headings: scalar, land-use, resource-use, temporal and population. The scalar and land-use categories are both spatially derived, the resource and population parameters relate to societal characteristics and the temporal parameters affect potential future time-frames.

2.1 Scalar parameters

Carrying capacity assessment, by definition, necessitates the delineation of geographic boundaries within which the population is relatively self-reliant for their resources. Politically-dictated delineation is a common method of achieving such small-scale boundaries, with the carrying capacity modelling of the Douglas (Banfield, 2000) and Noosa Shires (Summers, 2004) highlighting this approach. Politically defined boundaries are susceptible to alteration, complicating future analysis (Lane, 2010) and may not define areas of land best suited to supporting a relatively self-sufficient population. Consequently, topographically defined boundaries are more likely to offer long-term and practical landscape delineation. In Australia, catchment areas defined by watersheds are being recognized as useful divisions of the landscape, particularly in addressing land degradation problems (Williams and Walcott, 1998).

While aiming to provide modelling at a number of concurrent geographic scales, ultimately, the key determinant for landscape boundary delineation for the Dashboard model was the availability of Australian Bureau of Statistics (ABS) agricultural yield data (Australian Bureau of Statistics, 2006b). Given that this data is pivotal in the estimation of carrying capacity, the Dashboard's scale of analysis was matched to that of the ABS datasets. Currently ABS agricultural production data is collected by a nation-wide census (Australian Bureau of Statistics, 2008a) every five years (e.g. 2001, 2006, and 2011) while representative sample surveys (Australian Bureau of Statistics, 2011b) are used on a yearly basis between censuses. Regional Natural Resource Management Area (NRM) data is a recent addition to ABS's datasets. Although state and territory boundaries influence NRM delineation, they are generally based on catchments or bioregions, so are well suited to carrying capacity analysis. The 52 NRMs, together with seven states and Australia as a whole make up the 60 zones incorporated into Dashboard modelling (Figure 1).

In accord with Peters et al. (2007) who utilised five years of agricultural data for their carrying capacity assessment of New York State (1999 – 2003), modelling for the Dashboard used five years of ABS agricultural data (2006-2010) in order to derive average yield values for each crop. Given that yield data can fluctuate from year to year, the approach of Peters et al. (2007) to average a number of years of production provided a reliable methodology for accommodating such variability. However, it is important that the years used to gauge this average are in fact indicative of likely future yields. Given that climatic conditions, particularly rainfall, are key determinants of agricultural production (Wimalasuriya et al., 2008), an analysis of climatic data was undertaken for the years 2006 to 2010 to ascertain if they were typical. Records from the Australian Bureau of Meteorology (Table 1) show that this period was in fact reasonably representative of the long-term average national rainfall.

The array of yield data, primarily from ABS sources, for the 60 zones and 134 resource commodities (e.g. apples, wheat, peanuts) resulted in a corresponding 8,040 pieces of 5-year average yield data, all calibrated to a common measure (tonnes per hectare).

2.2 Land-use parameters

Land availability according to its usage type is a key determinant of a region's carrying capacity. The Dashboard modelling accommodates five types of land-use: cropping, pasture, non-agricultural,[1] infrastructure and nature reserve. These land types are generally in accord with Peters' et al. (2007) approach which relies on three categories: land usable for any crop, land limited to perennial crops / pasture and land limited to pasture. Recent versions of Ecological Footprint models (Borucke et al., 2011) also use a similar categorisation of land-usage. For instance the Global Footprint Network (2012) incorporates five land-use categories: cropland, grazing land, fishing grounds, forest land, carbon footprint and built-up land. Compared to the Dashboard, these land-types generally align with cropping, pasture, non-agricultural and infrastructure land. At present the Dashboard includes only farmed rather than oceanic fish-grounds and land ascribed to carbon footprint by the Global Footprint Network would fall under one of the other Dashboard categories such as cropping land (in the case of biofuel production) or non-agricultural land (for timber

[1] Non-agricultural land was considered to be the land remaining after other categories were allocated so includes unprotected bushland and forestry areas.

production). While the Dashboard provides default land area amounts according to the five types of usage for all 60 zones, users can also adjust these values manually.

The data used to inform the Dashboard land-use parameters was largely drawn from ABS sources (2008b; c; 2010a; 2011a). While ABS agricultural commodity datasets provided sufficient information for cropping and pasture land, data for areas of nature reserve and infrastructure land were not included in this dataset so had to be derived from elsewhere. For instance, nature reserve areas were sourced from the Australian Collaborative Land Use and Management Program (2009) (ACLUMP) NRM datasets while land used for infrastructure was derived from ACLUMP (2010) national land-use datasets. The infrastructure land area amounts were derived only from national data because insufficient detail was given in the regional data. A total national figure was achieved through summation of the data for manufacturing, industrial, residential, services, utilities, transport, communication, mining and waste treatment. This value was then divided by the Australian population for a per person infrastructural land-use figure of 1606m^2. This value includes all residential land (963m^2 per person[2]) even though much of this land could potentially serve a productive purpose. To calculate the amount of residential land that could have productive potential we replaced the infrastructural residential land value with an estimate of the building footprint. Of the 17 Australian suburbs assessed by Hall (2008), an estimate of 223m^2 was made for the average residential dwelling footprint. According to Moroney and Jones (2006) the average paved area within residential lots is about 49m^2, giving a total of 272m^2 for the average residential land per lot alienated from productive usage. The ABS housing data (Australian Bureau of Statistics, 2008d) reports that (on average) 2.5 people live in each dwelling. By apportioning the amount of single storey and multistorey dwellings according to the same data, a total residential footprint of 89m^2

[2] This 963m^2 per person (residential land-use) reflects a large amount of land held in rural or semi-rural properties which are not considered farmland.

per person was derived, which, when combined with the other infrastructure data (Table 2) generates a total land-use area for infrastructure of 732m^2.

Based on Dashboard modelling, the land-use categories which significantly affect population carrying capacity are cropping and pasture land. However, an analysis of the two main sources of data (Australian Bureau of Statistics, 2008b; c; 2009a; Australian Collaborative Land Use and Management Program, 2009; Australian Bureau of Statistics, 2010a; 2011a), reveal discrepancies between these two sets which are largely attributed to differing methodologies for the collection of this data (Brough, 2012). For instance, the ABS data is based on surveys of only some areas for four out of five years and then a census of the entire nation on the fifth year, whereby ACLUMP's data are derived every few years by combining land tenure and other types of land-use data, fine-scale satellite data and field data (ABARES, 2011b). Essentially, this means that the ABS relies on land-users themselves to self-report while the ACLUMP data is based on expert opinion.

Comparisons of the land-use mapping systems reveal that both cropping land and pasture land are smaller in the ABS at the national scale (Table 3) and also generally in most NRM scales. Reasons for evident discrepancies between the ACLUMP and ABS datasets include changes in land-use over time, changes in boundaries and rotation of land-use between pasture, cropping and fallow. Ultimately the ABS set was integrated into Dashboard modelling in order to maintain consistency with the yield data because both datasets were sourced from the same Agricultural Commodities database.

2.3 Resource-use parameters

The Dashboard incorporates 17 different resource-usage parameters (Table 4), each affecting the population carrying capacity in different ways. The unit of measurement is given as a percentage of an overall amount. This approach was employed to allow users to most easily understand the parameter amounts. For instance, it is anticipated that few people might be aware of the amount of red meat that any one diet might contain, but that it is much easier to understand that of all the meat eaten, a proportion could be either red or white. Generally, data is sourced for the parameters representing consumption habits (such as diet, activity levels and textile usage) at a national scale reflecting an Australia-wide cultural consistency. Alternatively, data for parameters with direct impact on a particular landscape such as climate variability and irrigation use, are sourced from as small a scale as possible, for maximum regional accuracy. In the case of biofuel and organic production, small-scale data was not available so a national and international scale was subsequently utilised.

2.3.1 Climate variability

A methodology for the incorporation of long-term climate variability was developed for the Dashboard which relies on historic yield variance for a selection of staple crops. The ABS (2009b) has recorded yields for wheat, oats and barley since 1861. Based on this historic data, an estimate of long-term production was made for likely timeframes ranging from 1 to 150 years (Figure 2). Consequently, the Dashboard's Climate Variability parameter reduces carrying capacity by the percentage of anticipated production of the worst year within a given timeframe. For example, the lowest yields in 100 years for Queensland were 65% less than average, so the carrying capacity would reflect this lesser productivity. In this instance, it could be said that the carrying capacity estimate is anticipating a one in one hundred year event. The original data was only collected on a state-wide basis so all smaller NRM regions are estimates only, based on the state-based data. This extrapolation potentially limits the accuracy of results at the regional scale but was deemed necessary due to the lack of small-scale data.

2.3.2 Food - amount

While carrying capacity modelling implies complete resource self-reliance within any one region, this ideal does not always occur in a real-world setting because a population is rarely likely to be completely isolated from its neighbours suggesting that some form of trading may occur. For this reason, the Dashboard gives users the ability to account for some degree of importing and exporting of resources. In the case of food, first an anticipated amount of food consumption for the population is established and then users can stipulate whether they anticipate the population to produce more of less of this consumed amount. A choice of 0% thus suggests that all food is imported while 100% indicates that all food produced is consumed (complete self-sufficiency) and 500% (the maximum allowable in the Dashboard) suggests that the majority of food produced within the region is exported.

Modelling for the dietary components of the Dashboard was based on a recent study by the National Health and Medical Research Council (NHMRC) which developed a series of ideal diets for the Australian population to guide healthy, culturally and environmentally acceptable eating patterns (Byron et al., 2011). While Dashboard modelling aspires to similar aims, some aspects of the NHMRC data needed to be altered in order for it to be utilised effectively within a new context. For example, their diet modelling presented a variety of serving sizes for various age-groups where Dashboard modelling required a dietary structure for the entire population. Consequently, ABS demographic data (Australian Bureau of Statistics, 2010b) was used to match the amounts of foods suggested for each NHMRC age group against the proportion of people in that age group within the national population to derive a particular diet for the whole Australian demographic profile (Appendix A). Another mismatch between NHMRC modelling and Dashboard aims is its entire reliance on ideal diets rather than existing Australian eating habits, so it was necessary to source further data from an ABS study which examined the Australian diet (Australian Bureau of Statistics, 1995). In total, over 700 different food items such as six types of apples, 40 cuts of beef and over 150 types of vegetables were included in the Dashboard modelling.

2.3.3 Meat-eggs

Carrying capacity assessment models conducted by other researchers (Peters et al., 2007; Fairlie, 2010) have consistently found that animal products generally have a significant impact on carrying capacity outcomes so it was deemed important to address this aspect in a detailed manner.

The Meat-eggs parameter adjusts dietary protein sources from animal-based products to plant-based products while maintaining a similar level of both calories and protein throughout. This parameter alters the proportion of meat and eggs consumption in the population’s diet from 0% to 15% with zero representing a meat product-free vegan diet and 15% representing a high meat-content diet. The other key points in this range are 13% representing an estimate of current meat-egg consumption, 7.5% representing a healthy diet as modelled by the NHMRC (Byron et al., 2011), 2.5% representing a lacto-ovo vegetarian diet (vegetarian diet with no meat but including eggs and dairy) (Byron et al., 2011) and 1.5% representing a ovo-vegetarian diet (no meat or dairy but including eggs). A different study, the ABS National Nutrition Survey (Australian Bureau of Statistics, 1995), was utilised to reflect standard Australian dietary consumption patterns (13% meat-eggs diet). All other diets in the meat-eggs parameter range were extrapolated from the NHMRC and ABS research. This was achieved by first determining the percentage of meat and eggs that each of these three diets possessed, then adding or reducing the meat and eggs in alternate diets to arrive at the remaining 28 diets (there are 31 diets in total – a range of 0% to 15% with 0.5%

increments). In order to achieve a balanced dietary intake across all diets a similar amount of calories, protein, carbohydrates and fat (Food Standards Australia and New Zealand, 2008) was maintained throughout all diets considered healthy by adjusting various food components, predominantly the higher protein foods such as legumes, nuts and seeds, dairy and cereals. For diets with more than 7.5% meat and eggs, the levels of protein, carbohydrates and fat may not be considered as healthy because they reflect average Australian consumption patterns rather than recommended intake. In order to balance the diet, the amount of dairy varies considerably, in accord with extrapolations from the NHMRC diets. It should also be noted that as meat, eggs and dairy decrease in the diet, nuts and legumes increase considerably while vegetables and grains increase to a lesser extent (Figure 3).

2.3.4 Red meat

The Red meat category allows Dashboard users to regulate the proportion of red and white meat in the average diet of the population. Regardless of choices of red or white meat, the amount of meat remains the same (the amount of meat is altered in the meat-eggs parameter), only the proportion of the source of meat changes. Key points in this range are the 64% amount, marking current red meat consumption (Australian Bureau of Statistics, 1995) as well and the 48% amount, representing the consumption level recommended by the NHMRC (Byron et al., 2011).

2.3.5 Activity levels

The activity level of the population affects the amount of food that the population needs to consume because higher levels of activity require more energy and more calories (Byron et al., 2011). This parameter thus reflects the average level of physical activity for the population. It is based on three diets developed by the NHMRC

(Byron et al., 2011) for sedentary, moderate and high physical activity levels ranging from 1828 to 2760 kilocalories per person per day. The high level of physical activity is equated with more than 90 minutes of daily strenuous activity; the moderate level of physical activity is the equivalent of 30-90 minutes of daily strenuous activity; and a sedentary level of physical activity is less than 30 minutes of daily strenuous activity (Tontisirin and Haen, 2004).

The calculation of a population’s caloric intake is a common carrying capacity assessment method in determining overall food demand (Gutteridge, 2005) and varies not only across diets and activity levels but also due to cultural expectations. Kendall and Pimentel (1994) estimated that in 1994 an average American ate 771kg of food per year while the equivalent individual in China consumed only 479kg per year. Given such discrepancies in caloric intake, it is suggested that carrying capacity modelling based on actual diets will offer more accurate results that those merely relying on an overall estimate of food weight or caloric value.

2.3.6 Avoidable waste

The Dashboard uses the same approach as Peters et al. (2005) and assesses six points in the food service system where wastage can occur and estimated the likely weight loss in all 746 food items. The six types of losses are (in chronological order from production to consumption) primary to retail loss, processing loss, retail loss, consumer loss, cooking loss and inedible portions loss. There is potentially another category that could be described as farming production loss, which would include all farm-based impacts on productive yield such as climate, pests, weeds, handling and storage losses. The yield data collected by agencies such as the ABS (Australian Bureau of Statistics, 2011a) already accounts for these losses in that agricultural production is calculated at the farm gate (i.e. the amount of produce leaving the farm) rather than at the paddock level.

Primary to retail losses refer to the reduction in produce that occurs between the farm gate and the retail outlet, including transportation, storage and handling losses. No detailed analysis of food losses within the Australian context was found for this part of the food chain. However, a UN study of food losses (Gustavsson, 2011) suggests that North America, Australia and New Zealand might have similar wastage patterns. The main source of data was therefore drawn from a United States Department of Agriculture (USDA) report (Buzby and Wells, 2010).

The majority of the *processing losses* incorporated into the Dashboard modelling were calculated specifically for this research by referencing a wide variety of relevant sources (Appendix B). For example, for the calculation of losses in the processing of the six types of wheat produced in Australia, extraction rates were averaged across Graincorp's seven grain refineries (Graincorp, 2010). Another example is the 67 types of breakfast cereal incorporated into the Dashboard. In this instance, each cereal was examined for their constituent components (e.g. wheat, corn, sugar etc.) and an estimate of both the proportion of each component and their processing yield was made.

Retail losses refer to the food that is wasted between the arrival of products at retail outlets and its sale to customers. In the absence of detailed Australian data in this topic, Buzby's U.S. research (Buzby and Wells, 2010) was again employed. Buzby found that losses could be expected for all retail foods but that, not surprisingly, the more fragile and perishable foods such as paw paw (with a loss of 55%) had higher rates of loss than the non-perishable items such as nuts (with a loss of 6%). The average loss across all foods incorporated into the Dashboard is 10%.

Consumer losses occur both in households and food-service establishments such as restaurants and is characterised by wastage in storage, preparation, and uneaten portions. In the absence of detailed Australian data, U.S. data was again used. The report by Muth et al. (2011) commissioned by the USDA informed most of the consumer losses for foods in the Dashboard. Findings ranged from a 50% loss for Swiss cheese to an 8% loss for parmesan cheese. The average consumer loss across all foods incorporated into the Dashboard is 22%.

Cooking losses occur largely as a result of the reduction in the water content of foods once heated. Unlike consumer and retail losses, there is no tangible left-over portion that is discarded. Detailed data for cooking losses has been conducted in Australia by the Food Standards Australia and New Zealand so their Nutritional Database (Ausnut) (2008) was primarily used. Alternatively the U.S. studies by Kantor (1997) or Matthews and Garrison (1975) were also referenced. Examples of *cooking losses* include 39% for pork and 2% for eggs.

The *inedible portions loss* represents a form of wastage that cannot be salvaged for human consumption, but reduces the weight of food items between production and consumption nevertheless. Examples include banana peel (35%), prawn heads and shells (57%) and apricot pips (6% loss).

In total, the amount of avoidable waste currently generated in Australia as a proportion of all food produced is 12% but users have the ability to adjust this in a range from 0% to 20%.

2.3.7 Recycling

This parameter estimates resource usage when wastage from the avoidable waste parameter is recycled back into the food system, thus reducing overall food demand. It was identified that there are two ways in which to recycle this waste; as feed to animals and as fertiliser (in the form of compost) for plants. Incorporating the recycling of food into fertiliser proved problematic because no data could be found directly linking food waste to compost quantities, nor compost fertiliser application amounts to crop yields. On the other hand, direct causal links between animal feed requirements and animal weight gain have been well documented as feed conversion ratios (FCR) (Westendorf, 2000). Consequently, only the aspect of animal feed was incorporated into the Dashboard, not compost.

All edible waste including consumer, retail, processing and inedible portions are converted to FCRs in the recycling parameter under the assumption that it is evenly distributed to farm animals including pigs, chickens, ducks, turkeys, farmed fish and farmed seafood (Lane et al., 2013a). Consequently, an increase in this parameter generally improves carrying capacity by reducing the demand of other resources for the production of animal products.

At present a negligible amount of food waste is recycled back into the Australian food system at a commercial level (Cozens, 2012) partly because of the health risks to animals (e.g. foot-and-mouth disease) and humans (e.g. mad cow disease) associated with recycling animal products. In the Dashboard, a range of 0% to 100% recycling is offered. The 100% figure represents the recycling of all the population’s scraps, offcuts and uneaten portions, as calculated in the *avoidable waste* parameter.

2.3.8 Organic farming

This parameter allows users to stipulate the percentage of organic farming carried out in any region as a proportion of all agricultural production. At present, just over 12 million hectares of Australia’s agricultural land is under organic production (Kristiansen et al., 2010) (about 2%) slightly below the OECD average of 2.4% (Pillarisetti, 2002). While it was possible to find data on the prevalence of Australia-wide organic production, no data was available at smaller scales so for the purposes of the Dashboard, the national figure was assumed to also be representative of smaller areas.

In the absence of locally available data, yield comparisons between organic and conventional agriculture from other countries was used to inform an estimate of Australian organic yields (Lane et al., 2013b).

2.3.9 Irrigation

This parameter allows users to adjust the percentage of irrigated farmland as a proportion of all farmland within a region. Irrigating crops can have a significant effect on production with Trewin and Banks (2006) estimating that irrigated farms generate, on average, 55% more output per farm than farms which do not irrigate. Ideally, the calculation of the effect of irrigation should occur on a crop by crop basis, but in the absence of such data an overall figure of 55% was applied to all regions. At present 0.5% of Australia's farmland is irrigated (Australian Bureau of Statistics, 2006a), but data for both state and NRM irrigated land areas are also publicly available so the Dashboard reflects regional variations in this regard.

2.3.10 Liquid fuel

The Liquid fuel and Biofuel parameters deal with a population's consumption of energy. Energy is a master resource (Bradley and Fulmer, 2004) which underpins the effective production of other resources. While a full carrying capacity assessment might incorporate all aspects of a population's energy production and consumption, the Dashboard only deals with liquid fuel (petroleum and biofuels) which is currently used predominantly for transportation (ABARES, 2010a) rather than the generation of electricity. This focus on liquid fuels has been driven by the fact that biofuels have a direct impact on land usage which is the basis of carrying capacity modelling. On the other hand, the various current forms of electrical energy generation derived from coal, solar, wind and geothermal sources potentially have dual-use (e.g. wind turbines can be raised above farmland) and/or could have little influence on agricultural land (e.g. coal mines might be placed on poor-quality land), so are more difficult to assess.

The *Liquid fuel* parameter allows Dashboard users to stipulate the amount of liquid fuel consumed by a population each year, calculated on a per person basis. A range of zero to 3000 litres is offered and users are informed that the current average Australian consumption rate is estimated to be 2520 litres per person (ABARES, 2010a). This amount includes both personal usage (e.g. petrol used in individual's cars) and industrial usage (e.g. diesel used in mining trucks but distributed over the entire population) and represents both petroleum and biofuels. This parameter gives users the ability to increase or decrease the societal-wide consumption of liquid fuels implying either a more profligate or energy-conservative approach.

2.3.11 Biofuel

This parameter allows users to alter the proportion of biofuel compared to petroleum used by the population. A user's choice of 100% biofuel assumes that no conventional liquid fuel (petroleum) is consumed and users are informed that current Australian biofuel consumption is estimated to be 0.5% (ABARES, 2010a). While the previous parameter determines the amount of liquid fuel consumed, this parameter determines its source, thus offering users the ability to choose between renewable and non-renewable transport fuels. As a user increases the proportion of biofuel in the model, more land is allocated to its production (e.g. from sugar cane, cereals and natural oils) rather than to human food production, thus generally reducing carrying capacity.

2.3.12 Textiles - amount

The incorporation of textile usage into Dashboard modelling is similar in approach to that of liquid fuels: a per-person amount of resource consumption is established, then this amount is apportioned to various sources. The *Textiles – amount* parameter offers a range of zero to 30 kilograms, with 23 kilograms being the current average Australian consumption amount (Plastina, 2011). This amount includes both personal usage (e.g. clothing) and shared usage (e.g. office furnishings).

Once the source of textile fibre is established (in the next two parameters), the amount of land required to produce the fibre (e.g. cotton from broadacre land-use and wool from pasture land) is then calculated based on yield data from ABS sources (Australian Bureau of Statistics, 2008b; c; 2009a; 2010a; 2011a). When incorporating the amount of fibre required for societal consumption, it was also necessary to account for wastage in the process of cleaning, spinning and manufacturing in much the same way as wastage is incorporated into the calculation of food consumption.

2.3.13 Natural fibre

This parameter gives users the opportunity to stipulate the degree to which the population's textile usage is from natural or artificial sources. A user's choice of 100% natural fibre assumes that no synthetic fibre is consumed and users are informed that current Australian natural fibre consumption is estimated to be 50% (Plastina, 2011).

2.3.14 Wool fibre

This parameter separates the consumption of woollen textile consumption from cotton as a proportion of the natural fibre chosen by users in the previous parameter (*Natural fibre*). Even though flax (0.4%) and cellulose (4%) account for a minor proportion of natural textile fibre (Plastina, 2011), the vast majority is either wool or cotton so this parameter just focuses on the proportion of wool and cotton in fibre consumption. Users are informed that current Australian wool consumption is estimated to be 12% of all natural fibre (Plastina, 2011).

2.3.15 Timber

The timber parameter accounts for the amount of timber consumed by the population each year, calculated on a per person basis. This amount includes both personal usage (e.g. timber-framed house, firewood (Driscoll et al., 2000)) and shared usage (e.g. commercial timber-framed buildings). Given the lack of regional data for timber production, national data is used for the Dashboard modelling. For instance, it was found that at present over 22 million cubic metres (ABARES, 2011a) of timber are consumed in Australia each year, representing about one cubic metre per person. Production (8.9 cubic metres per hectare of trees (West et al., 2008; ABARES, 2011a)) and wastage (43% (ABARES, 2011a)) data are then applied to this consumption amount in order to determine a Dashboard land-usage figure for timber.

The inclusion of timber into carrying capacity modelling presents certain challenges. For instance, timber offers a variety of different functions such as a material for construction, energy (firewood), stationary and various other household and industrial items, each with varied degrees of importance to human survival. For simplicity, modelling for the Dashboard did not separate any of these choices for users.

Data availability was quite poor for timber production in Australia so in some cases local data was extrapolated to a national level (West et al., 2008).[3] and in other cases, national data was also assumed to be indicative of regional conditions (ABARES,

[3] An example of local data being extrapolated to a national level includes the firewood yield of Eucalyptus globulus plantations in the Murray-Darling basin.

2011a).[4] Both of these assumptions leave a margin for error but until accurate localised data is collected for timber yields, this was the best compromise available.

2.3.16 Infrastructure

This parameter estimates the amount of land required for built infrastructure calculated on a per person basis. This amount includes both personal requirements (e.g. residential) and shared usage (e.g. land required for commercial, industrial, public service, recreational, defence, utilities, transportation-communication, mining, waste and water storage usage). The range offered in the infrastructure parameter is from zero to 2000 square metres and the model offers users two key options in this range: an estimated average Australian area for built-on private residential land of 730 square metres (ABARES, 2010b) (excluding privately owned green space) and 1600 square metres (ABARES, 2010b) as the average Australian estimate including all green space.

2.3.17 Nature reserve

This parameter allows Dashboard users to stipulate the percentage of protected land as a proportion of all land in any given region. Defaults are provided for all 60 regions as an indication of the existing amount of land set aside for conservation purposes (ABARES, 2010b). This is the only parameter that allows users to directly dictate the amount of land used for a particular purpose. All other parameters do so though the calculation of land requirements for certain activities such as a population’s diet or textile usage. The *Nature reserve* parameter, on the other hand, is not a reflection of societal need but rather of ecosystem requirements so no intermediate calculation is necessary.

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[4] An example of national data being used for regional conditions includes national sawn log production yields.

2.4 Temporal parameters

A set of default resource parameter settings are offered to Dashboard users as a way to simplify initial choices and highlight short-term and potential long-term settings (Appendix C). The short-term defaults reflect current consumption and production estimates. However, the non-renewable resources that underpin our current lifestyle are by definition unsustainable so this configuration is titled short-term. Alternatively, another configuration of parameters reflecting potential resource constraints in the future is also offered as a long-term option. Each region has a different set of short-term and long-term default figures but many individual figures are the same (reflecting a common Australian consumption pattern).

While the estimation of short-term carrying capacity can be instructive for existing lifestyles, long-term carrying capacity assessments best predict sustainable societal behaviour. While Dashboard users can make their own predictions of potential future resource utilisation, it is anticipated that initially, they may be daunted by the number of parameters so a pre-determined set of choices are offered with a *Long-term default* option. These parameter settings aim to best predict a fossil-fuel free future but as with any future prediction, they are reliant on various assumptions (Lane et al., 2013a), some of which could be seen as speculative. Consequently, the Dashboard also allows users to alter any of the long-term default figures to match their own expectations.

2.5 Population parameters

In Dashboard modelling, Australia's population was not only re-apportioned according to its demographic profile (Appendix A), but also distributed into existing population numbers per zone. The national and state populations were readily sourced from ABS data (Australian Bureau of Statistics, 2011c), but the existing population for each of the NRMs was predominantly sourced elsewhere (Robins and Dovers, 2007).

3. Results and discussion

The Carrying Capacity Dashboard was released publicly online (http://dashboard.carryingcapacity.com.au/) on March 23, 2012 with an updated interface released on August 10, 2012 (Figure 4). Results from the short-term parameter settings show that according to the model, Australia at the national scale has a population carrying capacity of 40,450,144 people with the land required for food being 48.9%, biofuel 0.2%, textiles 2.2%, timber 1% and infrastructure 0.4% of all land.

3.1 Critical analysis of Dashboard parameters

A number of biophysical and societal constraints including water, food, energy, shelter, technology and trade have been incorporated into the Dashboard in a variety of ways.

Dashboard modelling suggests that food production uses about half of all land under current Australian resource usage parameter settings, so represents the most important component of a carrying capacity model. An increase in food production, which involves a shifting of land use from other parameters to food production, will increase the carrying capacity, enabling population increases. The complexity of modern diets means that an array of foodstuffs are best incorporated into modelling and as Peters et al. (2007) point out, complete diets and food systems are preferable to analyses based merely on basic staples or caloric intake. Dashboard modelling initially analysed five key diets (Australian Bureau of Statistics, 1995; Byron et al., 2011) as anchor points for 93 complete diets with three levels of caloric intake. The Dashboard also builds on

Peters et al. (2007) work by incorporating new parameters such as recycling, animal products and red meat proportions and by offering user interaction in the choice of parameter settings. At present these food-related choices are limited to pre-determined diets but this feature has the potential to be further expanded in future.

In Dashboard modelling, the irrigation parameter offers only a broad-brush approach with one Australia-wide estimate for maximum potential yield applied to all resource commodities. However, more detailed data highlighting differences in potential yield on a local food-by-food basis was not available at the time of modelling. Additionally, further research on the energy requirements of irrigation and subsequent knock-on carrying capacity impacts, would also improve this aspect of the modelling. For instance, if biofuel needed to be grown to fuel irrigation pumps, then this would reduce the amount of land available for crops, leading to a decrease in carrying capacity.

In the Dashboard, the constraint of energy was restricted to liquid fuel and to a limited extent, firewood (as part of the timber parameter) because these aspects are directly affected by the availability of productive land within a carrying capacity model. The methodology for their inclusion, with one parameter representing the amount of fuel used and the other, a measure of the proportion of biofuel within the liquid fuel mix, successfully captured the degree to which renewable and non-renewable fuel usage affects carrying capacity. However, an effective method of including coal, gas, solar photo-voltaics, wind, geothermal and hydro-energy was not found at this stage, so could be something to consider for future models. Concerning the timber parameter, a potential improvement for a more detailed model might be to differentiate between timber for firewood and timber of other items because users may choose to adjust the consumption level of each of these aspects independently of the other. For instance, users may wish to assume that a future society may need to increase its energy use from renewable sources such as timber, but decrease its use of construction materials. These materials such as concrete, steel, earth and brick are currently implicitly included in modelling by way of the land requirements for infrastructure (e.g. mining), but could potentially be made more explicit in the model.

In a method similar to that of the biofuel parameter, the resources incorporated into Dashboard modelling for textile utilisation aims to highlight impacts of renewable and non-renewable resources. For instance, the first two textile parameters (amount and natural percentage) mirror the approach taken for biofuel – first a per person consumption level is established and then the proportion of natural and artificial components of that amount are given. The textiles category also offers a third choice which proportions amounts of wool and cotton within the natural fibre category. This is an important inclusion as these are the two most commonly used forms of natural fibre and because wool requires pasture land and cotton requires cropping land, they each affect carrying capacity in different ways depending on land availability within any region. The methodology used for this textile section thus successfully correlates consumption habits with land usage requirements not only in the overall amount of land required but also in the type of land (e.g. cropping and pasture). One potential improvement, however, could be the inclusion of other materials apart from wool and cotton. This could include hemp, bamboo and flax even though at present these form less than one percent of consumed textile resources in Australia (Plastina, 2011).

The inter-connectedness of Dashboard parameters is another important carrying capacity assessment feature. For instance, when the adjustment of one parameter impacts another, an ideal model would accommodate such indirect responses. The Dashboard accommodates such inter-relationships in its dietary preferencing, wastage and recycling parameters. For instance, when a user chooses a region which is unsuited to particular crops, the dietary consumption components of the population are automatically adjusted to suit local availability (Lane et al., 2013a). Likewise, when a user adjusts the diet or wastage rate for a certain population, the amount of potential recycling is automatically adjusted based on the anticipated availability of recyclable material. Additionally, when a user choses a consumption pattern which increases the land usage beyond land availability for that particular land type, the next best land type is automatically utilised instead. For example, if red meat consumption pushes pastoral land usage above pasture land availability, then cropping land will automatically also be utilised in the model. These automatic indirect adjustments are important in simulating real-life prioritisation processes. However, further improvements could be made in the incorporation of energy in this regard. At present, no indirect relationships between the energy intensiveness of certain activities and the land required to perform them have been established in the Dashboard. For example, adjustments to irrigation rates could potentially affect energy required for water pumping, having subsequent impacts on land usage particularly if the user has also chosen a high proportion of biofuel consumption (Lenzen, 2012).

Lastly, trade between regions was successfully implied in the model but further work on this aspect could make it more prominent. For instance, at present, food imports and exports are incorporated into the food percentage parameter. If more than 100% is chosen, it is assumed that the additional portion is exported and if less than 100% is chosen, an importation of food is implied. This approach was possible for food where a minimum level of consumption can be assumed for a population (based on basic physiological requirements), but this is not the case for fuel, textiles or timber consumption where minimum levels are less clearly defined. Consequently, in these instances, users are able to adjust consumption levels by overall amounts (e.g. kilograms of textiles, cubic meters of timber and litres of fuel) on a per person basis and existing Australian consumption amounts were offered as benchmarks for users to gauge any increase or decrease from current levels. This approach successfully allows each user to make informed choices but actual trading of materials is only implied. For instance, if a population intended to export half the timber in its zone, the user would currently need to calculate the amount of timber required per person and then double this amount. While this approach does allow for trade, an approach which mirrors the more overt food percentage parameter, would allow users to stipulate imports and exports directly. This methodology could potentially be applied to the fuel, textiles and timber parameters.

3.2 Limitations of data availability

Data availability is crucial to the successful incorporation of relevant and accurate carrying capacity modelling parameters. The availability of agricultural yield data is a fundamental constraint and the development of the Dashboard was limited to the scales at which such data has been published in Australia. Likewise, insufficient detail in land-use data, land suitability mapping and infrastructural requirements, all imposed constraints on the development of the model.

This research discovered significant discrepancies between two reputable sources of land-use data in Australia (Australian Bureau of Statistics, 2008b; c; 2009a; Australian Collaborative Land Use and Management Program, 2009; Australian Bureau of Statistics, 2010a; 2011a) and ultimately the decision to utilise the ABS figures was made on the basis of consistency with other data-sources rather than evidence of accuracy, so a revalidation of this source may be required in the future. While the ABS dataset maps existing land-use areas, it was not possible to incorporate potential future land-usage into the Dashboard. This would have involved the inclusion of land suitability mapping highlighting which pieces of land might be able to be converted from existing uses to other uses such as from pasture to cropping land.

While some land suitability mapping has taken place in Australia, as yet, this data has not been converted into NRM regionally-focused land boundaries (van Gool et al., 2005), is state based, classification systems are inconsistent (Australian Government, 2011) and has not been conducted for all parts of Australia (Australian Government, 2011).

More accurate regional analysis would improve the methodology for the estimation of infrastructural land-usage, but as this data was unavailable, only indicative figures for various suburbs were used in the calculation of dwelling footprint rather than a nation-wide analysis. It was also assumed that these nation-wide statistics are indicative of dwelling sizes and densities for all regions. Additionally, even once it was established that only $89m^2$ of the estimated total per person residential land amount of $963m^2$ was alienated from agricultural production, the quality of the remaining $874m^2$ was not able to be determined as it appears that no research has been done on this topic. Consequently, for modelling purposes, this land was placed in the non-agricultural category which only allows the model to utilise it for timber production. Future detailed analysis of the quality of residential open-space could mean the transfer of this land portion to pasture or cropping land, thus increasing carrying capacities for each region.

3.3 Components absent from model

While the Dashboard incorporates the parameters deemed essential for a resource-based carrying capacity assessment model, some resourcing needs have been given less emphasis, some have been incorporated into groupings which may obscure their relevance, while other parameters have not yet been introduced. For instance, while the Dashboard accounts for climate variability based on historic data, it does not yet address the potential impacts of future anticipated climate change and sea level rise. Alternatively, a resource which is integral but obscured in modelling is water. Rainfall and water storage capacity play significant roles in determining the carrying capacity of any landscape (Chisholm, 1999). However, in most cases, water availability is masked somewhat by the yields evident in the food supply and the technology of water capture, storage and irrigation (Cohen, 1995). In a comparison of water requirements for drinking and agricultural purposes, it is the latter which is by far the thirstier. For instance, Cohen estimates that the amount of water required for the production of one kilogram of bread (one cubic metre of water) exceeds the amount of drinking water for one individual for an entire year (0.73 cubic metres) (Cohen, 1995). It was thus considered that evidence of sufficient supplies of water for growing food is also likely to indicate sufficient supplies of water for drinking purposes, and as such the parameter of rainfall is only explicitly incorporated into Dashboard modelling in the irrigation parameter. Additionally, each zonally-attributed crop yield reflects inherent climatic and rainfall constraints and the infrastructure parameter also includes land used for water storage such as reservoirs.

One significant food resource absent from the Dashboard modelling is wild-caught seafood. Currently, all seafood included in the modelled population's diet is derived from farmed fish-stocks. This approach is reasonable for land-locked areas without access to marine resources. However, despite evidence of global marine fish-stocks declining (Dilworth, 2010), they are a renewable resource which coastal regions, in particular, could be expected to continue harvesting long-term, even if this is at lower levels than currently achieved. Consequently, a more detailed and comprehensive carrying capacity model might expand the boundary of coastal regions to also include a certain amount of marine area from which seafood could be harvested.

Another omission from the Dashboard is energy sources other than liquid fuel and firewood such as solar photo-voltaics, wind and geothermal. The reasons for this omission include the difficulty of accurately calculating the energy they may generate long-term in the absence of accompanying fossil-fuel energy as well as the potential for these energy sources to be used in tandem with other land-uses such as wind turbines over grazing land. However, it is envisaged that with further research, these difficulties may be overcome and other sources of energy may be incorporated into Dashboard modelling in future.

A further omission from Dashboard modelling is that of alternate agricultural production systems other than conventional farming and organics. For instance, multi-cropping systems such as permaculture were offered as an option in Fairlie's (2007) carrying capacity model. However, Fairlie himself describes his calculation relating to the permacultural closed-loop nitrogen cycle as, complicated and broad-brush (Fairlie, 2007). Whereas organic production was incorporated into Dashboard modelling by comparing conventional and organic yields, such comparisons are more difficult between intercrop and monoculture approaches because the total long-term yield over the whole system needs to be taken into consideration (Brown, 2003). Unfortunately, little research has been undertaken on the productivity of such systems in both Australia and other parts of the world so these alternate agricultural systems have currently been left out of Dashboard modelling (Lane et al., 2013b).

4. Conclusion

The Carrying Capacity Dashboard has incorporated the basic human resources essential for a population's physical survival including food, water, shelter and energy. While in some instances constrained by the availability of relevant data, this model highlights how each basic resource can be accommodated in the Australian context.

Carrying capacity assessment models have not yet gained the prominence of Ecological Footprint analyses such as the Global Footprint Network (2011). Part of the impediment for a more widespread adoption is the fact that each location requires the development of individualised carrying capacity modelling incorporating specific localised production yields. While the collection and collation of such data requires significant investment of time and energy, the process of modelling itself need not differ significantly between models. The publication of not only the results drawn from carrying capacity assessments, but also discussion around the incorporation of parameters and methodological processes (Lane et al., 2013a) thus has much validity. The Carrying Capacity Dashboard is one such example featuring replicable approaches for future carrying capacity assessment modelling in other regions and other scales of analysis.

References

ABARES, 2010a. Australian energy resource assessment. Commonwealth of Australia.

ABARES, 2010b. Land use of Australia. Commonwealth of Australia, Canberra, pp. 2005-2006 dataset.

ABARES, 2011a. Australian forest and wood products statistics, September and December quarters 2010, Canberra.

ABARES, 2011b. Guidelines for land use mapping in Australia: principles, procedures land definitions, Canberra.

Australian Bureau of Statistics, 1995. National Nutrition Survey - Foods Eaten - Australia, Commonwealth of Australia.

Australian Bureau of Statistics, 2006a. Characteristics of Australia's Irrigated Farms, Australian Government, Canberra.

Australian Bureau of Statistics, 2006b. Survey Participant Information - Agricultural Surveys. Australian Government, Canberra.

Australian Bureau of Statistics, 2008a. Agricultural Census. In: Australian Bureau of Statistics (Editor). Australian Government, Canberra.

Australian Bureau of Statistics, 2008b. Agricultural Commodities: Small Area Data, Australia, 2005-06. Commonwealth of Australia, Canberra.

Australian Bureau of Statistics, 2008c. Agricultural Commodities: Small Area Data, Australia, 2006-07. Commonwealth of Australia, Canberra.

Australian Bureau of Statistics, 2008d. Australian social trends, Housing, Table 1 Housing National Summary, 1997-2007, Canberra.

Australian Bureau of Statistics, 2009a. Agricultural Commodities Australia 2007-08. Commonwealth of Australia, Canberra.

Australian Bureau of Statistics, 2009b. Historical Selected Agricultural Commodities, by State (1861 to Present), Commonwealth of Australia, Canberra.

Australian Bureau of Statistics, 2010a. Agricultural Commodities Australia 2008-09. Commonwealth of Australia, Canberra.

Australian Bureau of Statistics, 2010b. Australian Demographic Statistics, Commonwealth of Australia, Canberra.

Australian Bureau of Statistics, 2011a. Agricultural Commodities Australia 2009-10. Commonwealth of Australia, Canberra.

Australian Bureau of Statistics, 2011b. Agricultural Survey, Australian Government, Canberra.

Australian Bureau of Statistics, 2011c. Australian Demographic Statistics, Commonwealth of Australia, Canberra.

Australian Collaborative Land Use and Management Program, 2009. Land Use Reporting, Bureau of Rural Sciences, Canberra.

Australian Collaborative Land Use and Management Program, 2010. Land Use of Australia, Version 4, 2005/2006, Bureau of Rural Sciences, Canberra.

Australian Government, 2011. A stocktake of Australia’s current investment in soils research, development and extension: A snapshot for 2010-11. Department of Agriculture, Fisheries and Forestry, Canberra.

Banfield, K., 2000. Recognising Ecological Obligations in Planning. RAPI Limits to Growth Forum. Institute for Sustainable Futures, Coffs Harbour.

Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., Lazarus, E., Morales, J.C., Wackernagel, M. and Galli, A., 2011. Accounting for demand and supply of the Biosphere’s regenerative capacity: the National Footprint Accounts’ underlying methodology and framework, Global Footprint Network, Oakland, CA.

Bradley, R.L. and Fulmer, R.W., 2004. Energy: The Master Resource. Kendall/Hunt Publishing Company, Dubuque.

Brough, D., 2012. Discrepancy between ABS and ACLUMP land-use datasets. Brisbane.

Brown, A.D., 2003. Feed or feedback: agriculture, population dynamics and the state of the planet. International Books, Netherlands.

Buzby, J.C. and Wells, H.F., 2010. Food Availability (Per Capita) Data System. US Department of Agriculture.

Byron, A., Baghurst, K., Cobiac, L., Baghurst, P. and Magarey, A., 2011. A new food guidance system for Australia – Foundation and Total Diets. Revised draft report for public consultation, National Health and Medical Research Council.

Chisholm, A., 1999. Land, resources and the idea of carrying capacity. Business Council of Australia Papers, 1:19-26.

Cohen, J., 1995. How Many People Can the Earth Support? W. W. Norton, New York.

Cozens, M., 2012. Disposal of food waste. Queensland Government, Brisbane.

Dilworth, C., 2010. Too smart for our own good: the ecological predicament of humankind. Cambridge University Press, Cambridge.

Driscoll, D., Milkovits, G. and Freudenberger, D., 2000. Impact and Use of Firewood in Australia, CSIRO Sustainable Ecosystems, Canberra.

Fairlie, S., 2007. Can Britain Feed Itself? The Land, 4:18-26.

Fairlie, S., 2010. Meat: A benign extravagance. Permanent Publications, East Meon, UK.

Fearnside, P., 1986. Human carrying capacity of the Brazilian rainforest. Columbia University Press, New York.

Food Standards Australia and New Zealand, 2008. AUSNUT07 Australian Food, Supplement & Nutrient Database, FSANZ, Canberra.

Global Footprint Network, 2011. Footprint Calculator. Global Footprint Network, Oakland, CA.

Global Footprint Network, 2012. Application Standards. Global Footprint Network, Oakland, CA.

Graincorp, 2010. Graincorp Harvest Report 09/10, Sydney.

Gustavsson, J., 2011. Global food losses and food waste, FAO, Dusseldorf.

Gutteridge, M., 2005. Ecological footprint and carrying capacity studies of South East Queensland: a comparison and discussion of results. Department of Natural Resources and Mines, Queensland Government, Brisbane.

Hall, T., 2008. Where Have All the Gardens Gone? Australian Planner, 45:30-37.

Hardin, G., 1986. Cultural carrying capacity - a biological approach to human problems - AIBS News. BioScience, 36:599-606.

Holmgren, D., 2002. Permaculture: principles & pathways beyond sustainability. Holmgren Design Services, Hepburn.

Hopfenberg, R. and Pimentel, D., 2001. Human Population Numbers as a Function of Food Supply. Environment, Development and Sustainability, 3:1-15.

Hopkins, R., 2011. The Transition Companion: Making Your Community More Resilient in Uncertain Times. Chelsea Green Publishing Company, Totnes.

Kantor, L., Lipton, K., Manchester, A. and Oliveira, V., 1997. Estimating and Addressing America's Food Losses, US Department of Agriculture, Washington DC.

Kendall, H.W. and Pimentel, D., 1994. Constraints on the Expansion of the Global Food Supply. Ambio, 23:198-205.

Kristiansen, P., Bez, N., Mitchell, A. and Monk, A., 2010. Australian Organic Market Report 2010, Biological Farmers of Australia, Chermside.

Lane, M., 2010. The carrying capacity imperative: Assessing regional carrying capacity methodologies for sustainable land-use planning. Land Use Policy, 27:1038-1045.

Lane, M., 2012. Carrying Capacity Dashboard - http://dashboard.carryingcapacity.com.au/. QUT, Brisbane.

Lane, M., Dawes, L. and Grace, P., 2013a. Construction methodology of a resource-based carrying capacity assessment model: an Australian case study. Environmental Modelling and Software, Submitted.

Lane, M., Dawes, L. and Grace, P., 2013b. Organic agriculture in human carrying capacity modelling. Renewable Agriculture and Food Systems, To be submitted.

Lenzen, M., 2012. Carrying capacity dashboard. In: M. Lane (Editor). Personal communication, Brisbane.

Matthews, R. and Garrison, Y., 1975. Food yields summarized by different stages of preparation US Dept of Agriculture, Washington DC.

Melrose, J. and Delepart, D., 2012. Hawai‘i County Food Self-Sufficiency Baseline 2012, University of Hawai‘i, Hilo.

Moroney, J. and Jones, D., 2006. Biodiversity Space in Urban Environments: Implications of Changing Lot Size. Australian Planner, 43:22-47.

Muth, M.K., Karns, S.A., Neilsen, S.J., Buzby, J.C. and Wells, H.F., 2011. Consumer-Level Food Loss Estimates and their use in the ERS Loss-Adjusted Food Availability Data, US Department of Agriculture, Washington DC.

Peters, C.J., Bills, N.L., Wilkins, J.L. and Fick, G.W., 2009. Foodshed analysis and its relevance to sustainability. Renewable Agriculture and Food Systems, 24:1-7.

Peters, C.J., Wilkins, J.L. and Fick, G.W., 2005. Input and Output Data in Studying the Impact of Meat and Fat on the Land Resource Requirements of the Human Diet and Potential Carrying Capacity: The New York State Example CSS Research Series Department of Crop and Soil Sciences, pp. 1 - 25.

Peters, C.J., Wilkins, J.L. and Fick, G.W., 2007. Testing a complete-diet model for estimating the land resource requirements of food consumption and agricultural carrying capacity: The New York State example. Renewable Agriculture and Food Systems, 22:145-153.

Pillarisetti, J.R., 2002. World Trade in Environmentally Sustainable Agriculture Products: Policy Issues for Australia. Journal of Economic and Social Policy, 7.

Plastina, A., 2011. World Apparel Fiber Consumption Survey, FAO/ICAC, Washington DC.

Robins, L. and Dovers, S., 2007. NRM Regions in Australia: the ‘Haves’ and the ‘Have Nots’. Geographical Research, 45:273-290.

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

Tontisirin, K. and Haen, H.d., 2004. Human energy requirements, Food and Agriculture Organization of the UN, Rome.

Trewin, D. and Banks, G., 2006. Characteristics of Australia's Irrigated Farms: 2000-01 to 2003-04, Australian Bureau of Statistics, Canberra.

van Gool, D., Moore, G. and Tille, P., 2005. Land evaluation standards for land resource mapping. Resource Management Technical Report, 298.

Wackernagel, M., 1994. Ecological footprint and appropriated carrying capacity: a tool for planning toward sustainability, University of British Columbia, Vancouver.

West, P.W., Cawsey, E.M., Stol, J. and Freudenberger, D., 2008. Firewood harvest from forests of the Murray-Darling Basin, Australia. Part 2: Plantation resource required to supply present demand. Biomass and Bioenergy, 32:1220-1226.

Westendorf, M.L., 2000. Food Waste to Animal Feed. John Wiley & Sons, Ames.

Whyte, J. and Beuret, N., 2004. Carrying Capacity and Borders. Chain Reaction, Winter:28-29.

Williams, R. and Walcott, J., 1998. Environmental benchmarks for agriculture? Clarifying the framework in a federal system - Australia. Land Use Policy, 15:149-163.

Wimalasuriya, R., Ha, A., Tsafack, E. and Larson, K., 2008. Rainfall Variability and its Impact on Dryland Cropping in Victoria. 52nd Annual conference of the Australian Agricultural and Resource Economics Society, Canberra.