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Can urban agriculture usefully improve food resilience? Insights from a linear programming approach

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Abstract

Rising food prices and economic stagnation mean that access to affordable, nutritious food is a real problem, even in high income countries such as the USA and Australia. It is claimed that urban agriculture (UA) reduces food costs and therefore has a role in improving household resilience during economic hardship. However, there is scant data to suggest that UA can appreciably improve household self-sufficiency in a crisis.

This paper addresses the gap between claims and reality when it comes to UA actually reducing food costs. Using Linear Programming (LP), factors such as crop yields, food prices and inputs (such as irrigation water) can be quantified realistically, and an objective (e.g. overall diet cost) can be optimised. Constraints are applied to force the UA production regime to conform to a balanced diet. Subject to these constraints, optimisation yields a best-case estimate of the outcome, so can be seen to provide a “cautiously optimistic” result.

The model is run for a case study in Adelaide, South Australia, and results suggest a typical high meat consumer could reduce their food cost by approximately 10% with substantial home food production (including intensive poultry rearing for meat). Meanwhile, a shift in diet towards vegetarianism would deliver twice the saving, with a further 10% achievable through UA. In the context of resilience, the results suggest that households could save a modest amount of money through dietary change and by growing some of their own food. The modelling revealed a trade-off between cost-saving and self-sufficiency (measured as percentage of home-grown dietary protein), but growing 10-15% of dietary protein on 40 m^2/person appears plausible without sacrificing financial savings.

Optimisation represents a quantitative framework that is suitable for a variety of extensions to help ground claims being made around UA and local food production, such as investigating the potential for reducing dependence on transport by provisioning food from within and around a city. The model would be greatly improved with more accurate data on yield, water and fertiliser inputs.

Introduction

Access to nutritious food at an affordable price is central to food security. The convergence of rising food prices with persistent economic stagnation and declining performance in traditional urban industries (such as manufacturing) mean that this is a real problem, even in high income countries such as the USA and Australia. Against this rather bleak setting, there is hope that a resurgence of urban agriculture (UA) may provide a bounty of healthy food and ease cost-of-living pressures at the same time (Wise, 2014). Grewal and Grewal (2012) claim that a small city such as Cleveland (USA) could potentially become self-sufficient in fresh produce, poultry, eggs and honey by growing food in vacant lots and rooftop hydroponic farms. Food production in cities has long been popular, with a commonly claimed advantage being that "home-grown" produce can appreciably reduce food costs (Baylock & Gallo, 1983; Patel, 1991; Ghosh *et al.*, 2008; Gray *et al.*, 2014).

Unfortunately there appears to be a gap between claims and reality when it comes to UA making a useful dietary contribution and actually reducing costs, for instance when considering the high cost of urban water required to irrigate crops (Ward et al., 2014b). In some cases, proponents of UA present a production model that either misses key costs (especially water) or assumes inputs will be available for free. For instance, in the popular "SPIN Farming" model proposed by Satzewich and Christensen (2011), both water and nutrients are assumed to be available at negligible cost. While in isolated instances it is possible for a food-growing enterprise to take advantage of, say, a local restaurant's waste to make compost, if the vision is ultimately for city-scale uptake of UA (as in the proposal of Grewal and Grewal, 2012) then these inputs will need to be costed competitively.

In general, discussions of UA in the literature are not rigorously quantitative and tend to focus on less tangible, or indirect (but important nonetheless) benefits such as social wellbeing (e.g. Brown and Jameton, 2000). On the one hand, the paucity of quantitative analysis is perhaps understandable given the typically informal, private and decentralised nature of UA activity, with a lack of record-keeping on yields, water consumption, fertiliser use, and capital costs. But on the other hand, there are widespread claims being made that UA could have definite tangible benefits such as cost-savings, and should be in the suite of strategies employed to improve food security and resilience (e.g. to rising food prices) in post-industrial cities. Some of these claims draw on optimistic predictions of high yields from emerging technologies such as hydroponic and aquaponic systems (e.g. Gladek, 2011; Grewal and Grewal, 2012). The present study focuses on conventional soil-based production systems as the most appropriate platform to begin quantitative assessment of UA, upon which future studies (addressing novel new techniques) could be built.

In a substantive effort to address the gap in quantitative analysis, Ward et al. (2014a) developed a simplified model of UA production taking into account water and fertiliser costs, as well as feed costs for poultry. They used Linear Programming (LP) to find the optimal mix of fruits, vegetables, nuts and poultry products to achieve a certain objective – either minimising food costs or maximising self-sufficiency in protein – subject to food group constraints that crudely forced the optimised mix of foods to deliver a balanced diet. A crucial part of their analysis was that the optimisation included a wide variety of foods, some of which (e.g. dairy, fish, red meat and broadacre cereal crops) were assumed not to be produced by UA. The LP model could choose which foods to include in the diet, and of those, which were able to be (optimally) supplied using UA. In this way, the produce from UA was nested within an optimised whole diet to determine its relative impact on objectives such as diet cost. Constraints were applied to simulate dietary choices such as high, low or no meat intake.

The fundamental problem addressed by this paper is the lack of quantitative analysis, and the resultant tendency to either over- or understate the potential of UA to contribute to resilience. "Resilience" here is taken to mean "the ability to recover from a shock", and in this paper we are investigating whether UA might to improve household resilience specifically to a financial shock. Barthel and Isendahl (2013) provided a historical perspective of UA in cities of the Mayan and Roman civilisations, as well as urban farming in response to the breakdown in complex food supply chains, as has been observed in Cuba. They concluded that UA has been – and should continue to be – considered in the mix of strategies to improve the resilience of cities, but noted that the water and land resources for UA in modern cities are "vanishing on a grand scale".

The interplay between food prices, purchasing power, consumption and nutrition is complex, involving education and discretionary choices. For the purposes of modelling it is important to find simple, yet meaningful, surrogates that reduce the system to a tractable problem. Therefore, while we are interested in exploring the scenario of a loss of purchasing power as may occur, for instance, during a protracted economic recession, the modelling simply focuses on reducing the cost of food. It is assumed, therefore, that the most important and relevant aspects of such a complex economic scenario can be adequately summarised as the real food cost, and that efforts that are effective in reducing this cost are likely to be effective in a real world economic recession.

In this scenario, the "base case" food consumer has a high meat diet and sources a negligible amount of food from UA. We will show how LP can be used to:

1. Determine the base case optimal (least cost) diet
2. Test the potential impact on diet cost by growing some food with UA
3. Compare the savings from growing food with other dietary choices (e.g. reducing meat consumption)

We will conclude the discussion by presenting a range of useful future extensions to the model that could significantly inform and benefit research and practitioners in the food security and resilience fields.

Modelling method

The human diet has previously been formulated as a LP problem and solved using readily-available tools (Dietitians Association of Australia, 2011). Ward et al. (2014a) presented an optimisation model called Land Use Dietary Optimisation (LUDO). The present paper summarises the method and results from that study, and the reader is directed to the original paper for further details. The model is generic, to allow straightforward extension in future work. A parameter without a subscript indicates a global value (e.g. total area available per person, TA). Subscript x is used to denote zone-specific values, where $x = 1$ is the UA zone and $x = 2$ is the external zone. Parameters unique to each food item are denoted by subscript i. The subscript r denotes a specific dietary component (e.g. protein). The subscript k refers to a specific resource (e.g. irrigation water) used as an input for food production. The subscript t refers to a time period (e.g. season). The model was populated with 70 food items ($i = 1$ to 70), each with a set of properties as outlined in Table 1.

LP operates by varying a number of decision variables in order to obtain the optimal set of values that either minimises or maximises the objective function, subject to a range of constraints. A typical objective function in business may be maximising profit; in dietary LP analyses an example of an objective may be minimising departure from a mean observed diet (Darmon et al., 2003). The objective functions are summarised in Table 2.

Table 1. Food item properties required for LUDO model

Symbol	Units	Description
$D_{i,r}$	units/kg	Quantity of nutritional component *r* (e.g. protein, energy, or dietary servings in a specific food group) delivered per kilogram of food item *i*
V_i	$/kg	Retail value ($/kg) of food item *i*.
$Y_{i,x}$	kg/m^2/day	Direct yield of food item *i* when grown in zone *x* (the average daily yield is the total crop yield divided by 365)
$DA_{i,x,t}$	[-]	Vector of values (0 or 1) indicating the dietary availability of item *i* grown in zone *x* during time period *t*, to account for seasonality of produce
$GA_{i,t}$	[-]	Vector of values (0 or 1) indicating whether item *i* requires land during time period *t*, to account for items that are only planted during certain parts of the year
Z_i	m^{2}day/kg	Indirect area (m^2) external to the city required to support 1 kg/day of production of food item *i*.
$R_{k,i,x}$	units/kg	Quantity of resource *k* (units e.g. "litres" for irrigation water), consumed in zone *x*, to produce 1 kg of food item *i* when grown in zone *x*
$IR_{k,i}$	units/kg	Indirect quantity of resource *k* (units e.g. "litres" for irrigation water) consumed in the external zone, to produce 1 kg of food item *i* grown in the UA zone

Table 2. Objective functions used by Ward *et al.* (2014a)

Objective	Description
$\min(RA)$	Minimise the total required area (*RA*) of the diet.
$\min(S_k)$	Minimise the total consumption S_k of a particular resource *k* (such as irrigation water).
$\min\left(TV - E\right)$	Minimise the net cost of food, where *TV* is the total retail value of food in the diet and *E* is the net value of all food produced in the UA zone (both are averaged over all seasons.)
$\max\left(\frac{H_{r,x}}{TDL_r}\right)$	Maximise the proportion of component *r* in the diet (relative to the specified minimum intake TDL_r for that component) coming from food produced in zone *x*.

The decision variables in this optimisation are the array of consumption rates $F_{i,x}$, which influences every objective in Table 2. For instance, the required area *RA* for a given diet is obtained by summing the areas required to produce each food item *i* in each zone *x*, where each food item's area is derived from the yield ($Y_{i,x}$) and consumption rates specified by $F_{i,x}$. Likewise, the total resource footprint S_k is found by summing the inputs of resource *k* that would be required to support all consumption rates $F_{i,x}$. The total retail value *TV* is found by summing together each $F_{i,x}$ multiplied that food item's price (V_i). The net value of urban produce *E* is the retail value minus the costs of inputs (such as water and fertiliser) for consumption rates $F_{i,x}$ in the UA zone (x = 1). The total contribution to the diet $H_{r,x}$ from zone *x* is found by summing the consumption rates $F_{i,x}$ multiplied by each item's nutritional content $D_{i,r}$.

It can be seen that the objective functions in Table 2 all depend on aggregating information based on the $F_{i,x}$ array. The $F_{i,x}$ values represent the quantity (kg/person/day) of each food item *i* in the diet from each production zone *x*. The "UA zone" is a specified area (per capita) available for UA and could represent, for instance, part of a household backyard given over to food production, or an allotment or community garden plot. A generic "external zone" is assumed to exist outside the city, and this area can optionally be constrained (to control overall land footprint). The $F_{i,x}$ array is the set of decision variables that the LP model varies in order to deliver one of the four objectives in Table 2. For a given zone, the result of the LP analysis will be the set of optimised consumption rates and their respective production areas (Figure 1).

The third and fourth objectives in Table 2 are most directly relevant to the discussion of local food resilience, although the first two objectives are relevant to broader (national or global) questions of food security scale as they relate to carrying capacity. It is important to note that it is often not possible to optimise two objectives simultaneously – for example the diet can be optimised for minimum net cost, or maximum protein from the UA zone, but necessarily not both at the same time.

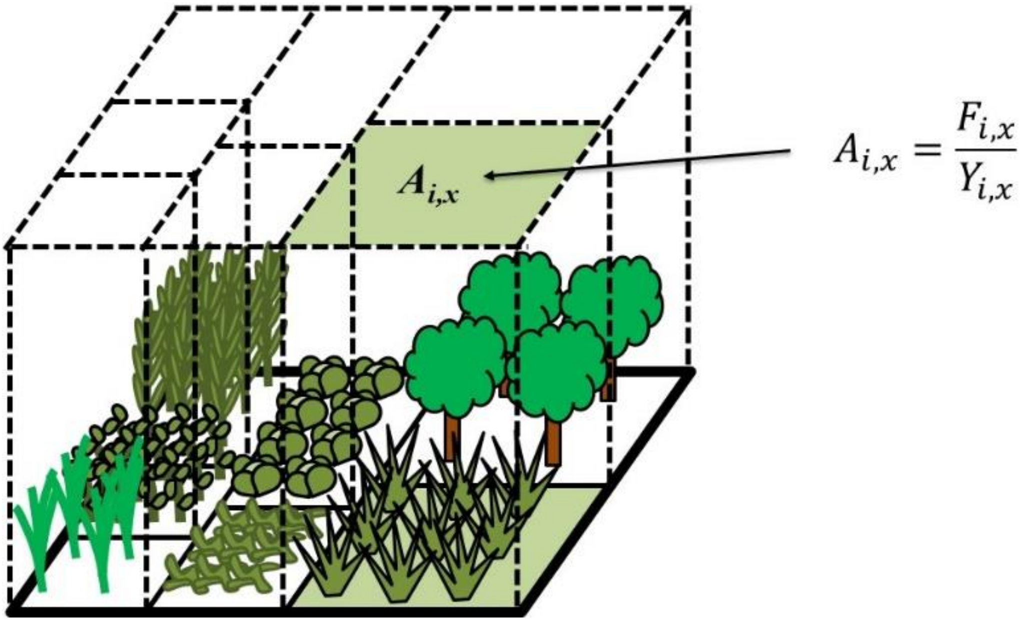


Figure 1 – conceptual model of food production in zone *x*, showing relationship between consumption rate ($F_{i,x}$), yield ($Y_{i,x}$) and resultant production area required ($A_{i,x}$) for each food item *i*. (For simplicity, seasonal effects are not shown here.)

LUDO included urban livestock as well as crops, and the area calculations broadly accounted for the external (indirect) land footprint for urban livestock, i.e. the land area required for grain used as chicken feed, and this was added to the overall dietary footprint.

To obtain practically useful results from an LP optimisation, constraints must be applied. Constraints are generally variables that must be less than, greater than or equal to a specified value and may relate to the decision variables ($F_{i,x}$ array), or to variables derived from them (such as overall dietary energy). In comprehensive dietary optimisation studies, the constraints have included overall vitamin and mineral intake to ensure the optimised diet delivers a balanced set of nutrients (e.g. Marten and Abdoellah, 1987). In LUDO, constraints are applied to ensure that the optimised diet:

- Remains within specified per-capita land and resource footprints;
- for practicality excludes certain specified foods from urban production (e.g. dairy, broadacre cereals);
- delivers a number of dietary servings per food group in accordance with dietary guidelines;

- delivers a daily intake of protein and energy within dietary guidelines; and
- includes a practical daily intake for each individual food item (i.e. prevent the program from selecting an excessive amount of any particular food item).

The mathematical derivations for the objective functions and constraints are all provided in an appendix by Ward et al. (2014a), and the reader is directed there for more detail.

Case study: Northern Adelaide, South Australia

Many of the parameters affecting the LP analysis are at least region-specific, and some vary at the site level. For instance irrigation water demand is calculated using local climate data, retail (supermarket) food prices may be similar across a relatively wide region, but the land available for UA may depend on the site. Which food items are able or unable to be produced in UA may depend on an individual site, or may be subject to regional effects such as policy or climate. Table 3 summarises the considerations and assumptions made in the data acquisition and modelling, including regional and local effects.

Ward et al. (2014a) demonstrated LUDO with an application to the Northern Adelaide area in South Australia. In this area, there is widespread socio-economic disadvantage (Pink, 2013) and local employment opportunities are decreasing due to declines in manufacturing (SA Government, 2013). Northern Adelaide is therefore a very appropriate setting to test the applicability of the LP framework to studies of food resilience, especially in terms of reducing exposure to food costs.

Constraints on food group representation in the diet were adapted from Dietitians Association of Australia (2011) and are given in Table 4. Minimum intake of discretionary food items such as butter and cooking oil, as well as spices, wine and beer, are included to simulate aspects of a typical Australian diet; none of these discretionary foods are required to make up a balanced diet, but all are likely to be eaten by a typical consumer and therefore affect both the daily nutritional intake and diet cost. Table 5 shows the assumed intake of discretionary items (applied as a lower constraint to the $F_{i,x}$ terms to ensure they are included in the diet). It should be noted that these constraints were included to add plausibility to the results on a macro level, in terms of a reasonable whole diet cost and footprint, but the specific details (such as exactly which spices are being consumed, or whether the consumer has equal quantities of wine and beer) are not central to the analysis.

Table 3 – Summary of data used in Northern Adelaide case study

Property	**Considerations / assumptions in scenario modelling**
Land available in UA zone	TA_1 (total area available in zone 1, UA) varied to test a range of possibilities including no UA.
Foods not able to be produced in UA	$TA_{i,1}$ (total area available for food item *i* in zone 1, UA) set to 0 for dairy products, pork, grazing livestock, broadacre cereals/legumes, sugar cane and bananas.
Crop yields	$Y_{i,1}$ (yield of item *i* grown in zone 1, UA) assumed to be equal to Australian national average from FAOSTAT (2013). $Y_{i,2}$ (yield of item *i* grown in zone 2, external) assumed to be equal to world national average from FAOSTAT (2013).
Meat yields	$Y_{i,x}$ obtained from industry sources. Beef and lamb assumed to be grazed extensively; poultry and pigs assumed to be grown intensively but indirect footprint applied to total production area to account for feed.
Seasonal availability	Year split into four seasons, affecting land area and dietary availability; externally-produced items assumed to be available all year (reflecting a globalised food supply) with the exception of fruit. Growing area varies over time according to the crop type.
Water input	$S_{1,i,1}$ (input of resource 1, water, for food item *i*, grown in zone 1, UA) calculated according to FAO56 method using crop coefficients from Allen *et al.* (1998) using local precipitation and reference evapotranspiration data; cost of resource input taken as current mains water rate. $S_{1,i,2}$ (input of resource 1, water, for food item i, grown in zone 2, external) assumed to be global average blue water footprint from Mekonnen and Hoekstra (2011, 2012)
Fertiliser input	$S_{2,i,1}$ (input of resource 2, fertiliser, for food item *i*, grown in zone 1, UA) assumed based on a uniform application rate and cost consistent with commercially available garden fertiliser. Fertiliser not considered for external zone in this analysis (only used to calculate input costs and net value for UA produce).
Nutritional content of food items	$D_{i,r}$ (protein and energy content) are taken from NUTTAB (2010), an Australian nutritional database. Each food item is assigned a dietary food group from the Australian Dietary Guidelines (NHMRC, 2013), and the servings/kg calculated depending on energy content of the food item and the energy per standard serving in the corresponding food group.
Nutritional constraints on diet	Upper and lower constraint values taken from the Dietitians Association of Australia (2011). Required dietary energy depends on age, sex, height and level of physical activity (NHMRC, 2013). Bounds for protein intake are the mass of protein required to deliver 10% (min) to 25% (max) of dietary energy (assuming 17 kJ per gram of protein).
Retail value	Prices for food items are taken as the current retail value (per kg), with data simply sourced from local online supermarkets and price assumed to be constant.

Table 4 – Food group intake constraints (from Ward et al., 2014a)

Dietary Food Group	(kJ/serve)	Lower (serves/day)	Upper (serves/day)
Dairy	600	1.5	4
Discretionary Choices	600	0	3
Fruit	350	2	4
Green and brassica vegetables	100	1	2
Legumes	350	0	6
Nuts and seeds	750	0	2
Orange vegetables	150	1	2
Other vegetables	100	1	2
Refined/low fibre cereals/grains	550	0	2
Starchy vegetables	250	1	4
Unsaturated oils/spreads	250	0	5
Wholegrain/high fibre cereals/grains	450	2	6
All Cereal (refined + wholegrain)	-	4	6

Table 5. Additional constraints at the individual food item level (from Ward et al., 2014a)

Food item	Min. intake (grams/person/day)
Olive oil	10
Butter	20
Beer	100
Wine	100
Coriander, dried	0.5
Cardamom dried	0.5
Chillies, dried	0.5
Garlic, clove	10
Basil, fresh	10
Pepper (Piper spp.)	0.5
Snack biscuits (savoury)	16
Cane sugar	5
Coffee, from beans	5
Tea, from leaf	5

According to Dietitians Association of Australia (2011), the lower constraint on red meat and poultry is zero, reflecting the prevailing nutritional wisdom that meat, *per se*, is not required to achieve a balanced diet. In the scenario being explored, however, we wish to take as a base case a "typical" Western consumer, with a diet rich in red meat and poultry. This is achieved by specifying alternative constraints on the meat food groups, using dietary consumption data from a comprehensive national dietary study (McLennan and Podger, 1999).

For the current paper, the base case scenario assumes no area is allocated to UA. The LUDO model is applied to determine the least-cost diet that satisfies these constraints. Then, to test the extent of cost savings that can be achieved through UA, a range of food garden sizes are tested without changing the dietary constraints. Following this, a *lacto-ovo* vegetarian diet is simulated and again optimised for least-cost, both with and without land for UA. Table 6 summarises the four scenarios.

Table 6 – dietary and UA zone constraints for scenarios

<table>
<tr><th>Scenario</th><th>Extra dietary constraints (servings/day)</th><th>UA zone area (m²/person)</th></tr>
<tr><td>Base case</td><td rowspan="2">Red meat: 2 (min.) to 3 (max.)
Poultry: 0.5 (min.) to 0.7 (max.)
Fish: 0.1 (min.) to 0.4 (max.)
Eggs: 0 (min.) to 0.5 (max.)</td><td>0</td></tr>
<tr><td>Base case + UA</td><td>5-300</td></tr>
<tr><td>Vegetarian (no UA)</td><td rowspan="2">Red meat: 0
Poultry: 0
Fish: 0
Eggs: 0.5 (fixed)</td><td>0</td></tr>
<tr><td>Vegetarian + UA</td><td>5-300</td></tr>
</table>

The garden sizes cover a range from 5 to 300 m^2/person, reflecting a broad but realistic variation in per capita access to land with food-growing potential. Based on typically small lot sizes in Northern Adelaide, it is likely that there is a practical upper limit to per capita food garden size at around 40 m^2/person (i.e. 160 m^2 of yard space given over to food production to support a household of four people). The reason for testing a wide range of garden sizes is that there are limited dietary opportunities to accommodate high-value crops (such as fresh herbs); therefore, it is expected that the specific crop mix that is optimal for a small garden will be quite different to that selected for a large garden, and that diminishing returns should be evident as garden size increases. Because the land availability is expressed as an area per person, the larger hypothetical garden sizes could be viewed as inclusive of multiple parcels of land, such as the household yard, roadside verge, community garden or allotment.

Results and discussion

The results presented here are a re-analysis of those presented by Ward et al. (2014a) and are intended to demonstrate an example of how LP can be used in studies of food resilience. All monetary values are presented in Australian Dollars.

Base case scenario

In the high meat diet, there are three red meat types that the model can choose from: beef, lamb and pork. Under a cost-minimisation objective with no constraints on land footprint, LUDO selects mostly beef, reflecting the fact that this has the lowest price ($10/kg for diced beef) at the time of the analysis. The minimum cost for this diet was $11.09/person/day and the supporting land footprint was 3.8 ha per person. It is possible to progressively constrain the available land footprint down to a minimum of 1.78 ha, but to do so the diet shifts from beef towards more expensive pork ($19/kg), pushing the cost to over $16/person/day. There is a continuum (but non-linear distribution) of possible optimal diets in between these extremes, with a "middle-of-the-road" solution identified with a per capita cost of $12.22/day and footprint of 1.88 ha.

According to the most recent survey of food expenditure in Australia, the average household (2.57 people) spends $204/week on 'food and non-alcoholic beverages' (ABS, 2011). This level of expenditure, after adjusting for inflation over four years, comes to approximately $12.30/person/day, so is broadly consistent with the cost predicted by LUDO. These results point to the possibility of LP offering a way to test conflicting objectives, such as minimising cost versus minimising land footprint. Clearly the results are highly dependent on the variety of meat products the model has to choose from, and there would be some benefit from including a wider range of low-value meat products, as well as increasing the range of meats available that have higher land-efficiency. However, the results give us a starting point for our scenario testing, and a minimum cost of $11.09/person/day will be used as the base case least-cost diet.

High meat + UA scenario

In this scenario, LP is used to determine (a) the best-case diet cost reduction, and (b) which items are selected for production in the UA zone, over a variety of garden scales. Optimisation for least-cost is not as simple as selecting the UA crops with the highest net value per unit area. To reduce overall cost below that of the base case (which has already been optimised for least-cost), the model must select foods for UA production that will displace costs the most efficiently in terms of meeting dietary constraints across the four seasons. The foods that displace cost the most efficiently are not necessarily those with the highest net value.

Table 7 shows the foods selected for UA and the resultant price reduction over the range of garden sizes. As the garden size increases, a wider variety of food can be grown, displacing some of the food in the diet and saving money. However, it is interesting to note that the main effect of growing food is to increase the gross value of the diet, so the net reduction in diet cost (relative to the base case) is less. A positive way to view this outcome is that UA has the potential to improve food variety and facilitates a higher value diet, and does so without incurring the additional cost. Beyond a UA area of 150 m^2/person, LUDO is unable to find any further opportunities for cost savings. This is because a substantial portion of the diet (including red meat, cereals and dairy) has been excluded from the UA zone.

It is worth noting that chicken meat has been included in this analysis using optimistic expectations of yield based on industry data from commercial free range poultry. As a result, chicken meat accounts for a substantial fraction of the value of food produced in the garden ($0.13/day at 20 m^2 UA area, and then $0.42/day for 40+ m^2). We acknowledge that the practicality of maintaining an intensive backyard poultry operation (including slaughtering chickens regularly) is questionable. The remaining scenarios consider a vegetarian diet where chicken meat is excluded.

Vegetarian (no UA) scenario

Faced with the need to reduce diet cost, an alternative to UA may simply be to adopt a cheaper diet. Here we see what LUDO delivers in terms of a theoretical least-cost diet, constrained to a lacto-ovo vegetarian specification (Table 6). A similar trade-off exists between land footprint and cost for vegetarian diets as was seen for high meat diets. However, in their modelled vegetarian diet both the land footprint and the overall cost were substantially lower than in the high meat diet. The least-cost diet came in at $8.90/person/day with a land footprint of 0.24 ha/person, a theoretical saving on land of more than 90% relative to least-cost diet in the base case. Optimising for land footprint, on the other hand, delivered a minimum area of 0.185 ha, but drove the cost up to $11.90.

The difference between the two least-cost diets (base case and vegetarian) is $2.19/person/day and the cost of the cheapest vegetarian diet is substantially less than the best result obtained in the base case + UA scenario ($9.72 at 150 m^2 of garden area). This suggests that a reduction in meat intake could be considered, at least alongside the option of growing food. It should be noted that alternative diets (such as moderate meat intake, or reduced dairy, etc.) can be easily tested by arbitrarily changing the minimum and maximum servings for the appropriate food groups (Tables 4 and 6).

The remaining scenario will investigate the combined impact of intake vegetarian diet and taking up UA.

Table 7 – Items selected for urban gardens (base case + UA scenario)

Garden size (m^2/person)	Items selected	Gross diet value ($/day)	Net value of UA produce ($/day)	Net diet cost ($/day)
0 (base case)	-	$11.09	-	$11.09
5	Fresh herbs, Eggs, Garlic, Broccoli, Lettuce	$11.37	$0.81	$10.56
10	+ Broad beans, Tomatoes	$12.03	$1.57	$10.45
20	+ Chicken meat, Carrots	$12.12	$1.82	$10.30
40	+ Cauliflower, Spinach [a]	$12.53	$2.54	$10.00
75	+ Green beans, Potatoes, Pumpkins, Oranges, Pears, Grapes, - Broccoli [b]	$12.99	$3.21	$9.77
150	+ Onions, Dried grapes, Broccoli, - Pears [b]	$13.28	$3.56	$9.72
300	[c]	$13.28	$3.56	$9.72

[a] Significant increase in chicken meat production from 20 to 40m^2.

[b] Certain items were selected for the UA zone at smaller garden sizes and deselected at medium-large garden sizes, due to complex interactions between seasonal availability of different crops and resultant optimal land allocation.

[c] No change when going from 150 to 300 m^2, as the cost-minimisation opportunities are exhausted at around 150 m^2

Vegetarian + UA scenario

Table 8 shows the breakdown of the UA regime at various sizes, when the diet is constrained to the lacto-ovo vegetarian specification. A similar trend occurs as was seen with the base case + UA scenario, in that the urban food production contributes more towards raising the gross value of the diet, and less to reducing the net cost. Without the opportunity to draw on high-yielding (and high net value) chicken meat, the overall economic potential for a vegetarian UA system is slightly less than in the base case. A similar pattern emerges in terms of which crops should be included in a UA regime at various garden sizes; in the vegetarian case, crops tend to be introduced at smaller garden sizes than in the base case as there is no need to preferentially allocate space to chicken meat. It is worth noting that the maximum specified dietary intake of (on average) 1 free range chicken egg per day can be achieved with approximately 3 m^2/person of space, whereas it takes around 35 m^2/person to supply the maximum intake of free range chicken meat. It is for this reason that vegetable crops emerged only in larger gardens in the base case.

As a strategy to reduce food costs, moving to a vegetarian diet could save 20% compared with a typical high meat intake diet; engaging in a modest amount of urban food production (say, 20 m^2 of garden per person) could yield a further cost saving of around 10%. Adopting larger-scale UA could deliver a more varied diet, but would do comparatively little to reduce food costs.

Table 8 – Items selected for urban gardens (vegetarian + UA scenario)

Garden size (m^2/person)	Items selected	Gross diet value ($/day)	Net value of UA produce ($/day)	Net diet cost ($/day)
0	-	$8.90	-	$8.90
5	Fresh herbs, Eggs, Garlic, Broccoli, Lettuce	$8.86	$0.82	$8.04
10	+ Broad beans, Tomatoes, Carrots, Onions	$9.31	$1.35	$7.96
20	+ Cauliflower, Spinach, Grapes, Oranges, Pears, - Tomatoes [a]	$9.80	$1.95	$7.85
40	+ Pumpkins [b]	$10.09	$2.38	$7.71
75	+ Potatoes, Dried Grapes	$10.81	$3.19	$7.62
150	+ Tomatoes, Apples, - Pears	$10.82	$3.20	$7.62
300	[c]	$10.82	$3.20	$7.62

[a] Certain items were selected for the UA zone at smaller garden sizes and deselected at medium-large garden sizes, due to complex interactions between seasonal availability of different crops and resultant optimal land allocation.

[b] Significant increase in orange and pear production from 20 to 40 m^2

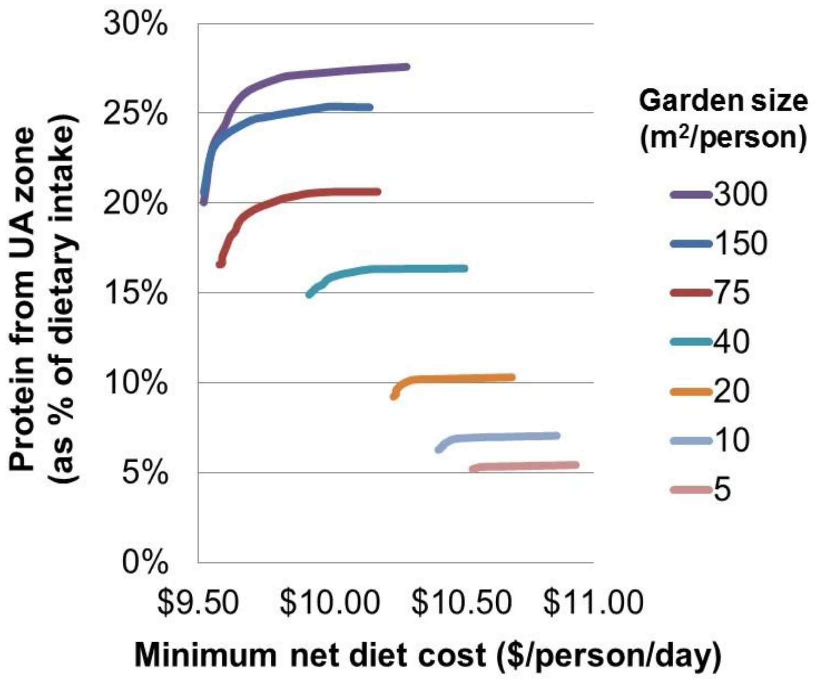
[c] No change when going from 150 to 300 m^2, as the cost-minimisation opportunities are exhausted at around 150 m^2

Reducing food costs vs self-sufficiency

One of the useful applications of LP is the ability to compare results from optimisation under competing objectives. Here we compare the least-cost objective (as discussed above) against an objective representing an alternative motivation for UA – maximising self-sufficiency. In their analysis, self-sufficiency was taken as the proportion of dietary protein coming from the UA zone.

Figure 2 shows the results of a comparison between minimising diet cost and maximising protein self-sufficiency. At the smallest garden sizes, there is little flexibility in terms of protein self-sufficiency, but as UA area increases beyond about 20 m^2/person the curves indicate a clear trade-off between the two objectives. The most important findings here are that (a) a modest degree of protein self-sufficiency is quite achievable, even without relying on chicken meat, but (b) increasing protein self-sufficiency can usually be achieved for a modest increase in diet cost. For instance, in the base case + UA scenario, at 75 m^2/person UA area may yield 17% protein under a least-cost objective, but to increase the protein to, say, 20% the diet cost would only increase by approximately $0.10/day. The larger the garden size, the greater the range of potential protein self-sufficiency.

(a) Base case + UA scenario



(b) Vegetarian + UA scenario

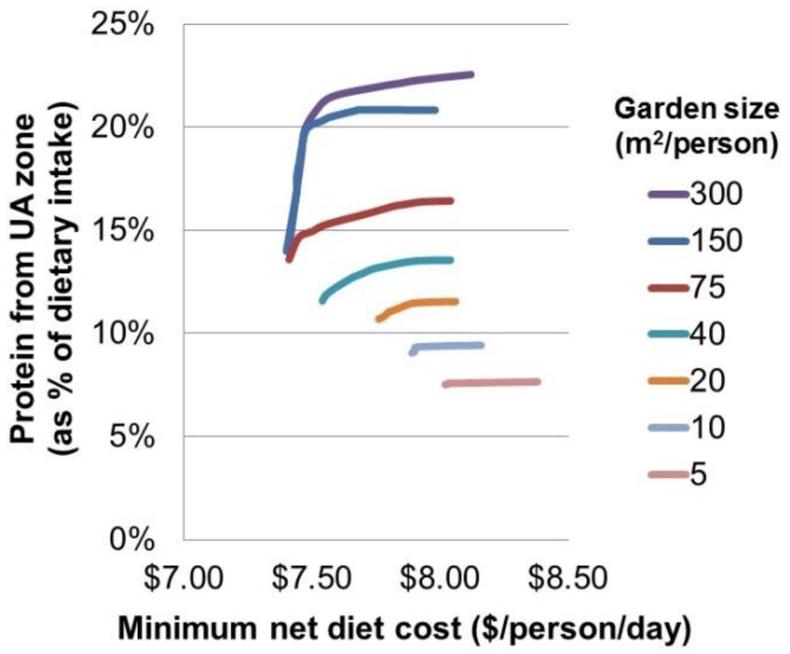


Figure 2 – multi-objective curves illustrating the trade-off between optimising for least-cost versus maximising self-sufficiency in protein, for (a) base case + UA scenario, and (b) vegetarian + UA scenario. From Ward et al. (2014a).

Figure 3 shows the different production areas allocated by LUDO under two different objectives (least cost and maximum protein self-sufficiency) – i.e. for opposite ends of the multi-objective curves in Figure 2. Under the high meat case, chicken meat emerges as the dominant mechanism for maximising protein self-sufficiency in small (5 m^2/person) and medium (20 m^2/person) gardens. On the other hand, if the objective is minimising cost, then several vegetable items are preferred for small gardens, although chicken meat is selected again for medium gardens. In the vegetarian diet, the absence of chicken meat leads to the selection of a range of vegetables. The graphs illustrate some key similarities and differences between the crops that are optimally selected to achieve each objective. Interestingly, chicken eggs are selected in all garden sizes, for both diets, and for both objectives. Substantial differences exist between optimal crop mixes for each objective, for instance the fact that almonds are selected for protein self-sufficiency but not for cost reduction, and while Spinach planted in March is selected for protein self-sufficiency, September Spinach is selected for cost reduction. These highlight some of the complexity that would be involved in the design of truly beneficial UA systems.

The model accounts for two physical resource inputs to UA: water and fertiliser (see Table 3). It is important to note that in the current analysis, these resources have not been constrained in terms of supply, but a realistic retail cost has been attached to each one to prevent unduly optimistic predictions of cost savings from UA. Ward et al. (2014b) showed, albeit without optimising the crop mix, that scaling up of food gardens across Australian cities could generate an increase in urban water consumption of 20-50%. If necessary, water supply could be easily imposed as a constraint in LUDO to force the optimisation to deliver crop mixes compatible with scarce water scenarios. The water consumption figures from the current analysis are given in Table 9 for a garden size of 40 m^2/person (the size used by Ward et al., 2014b). For the meat diet, when maximising protein self-sufficiency the model selects almost 100% chicken and egg production, with negligible associated water footprint. For cost minimisation in a meat diet, or for the UA supporting a vegetarian diet, substantially more water is required due to the increased dependence on plant crops. For Adelaide, household water consumption is approximately 200 L/person/day, so the numbers in Table 9 lend some support to the figures presented by Ward et al. (2014b).

Table 9 – Water use for a garden size of 40 m^2/person

Scenario	Objective	Water use (L/person/day)
Base case + UA	Min cost	36.0
	Max protein	2.93
Vegetarian + UA	Min cost	106.6
	Max protein	116.3

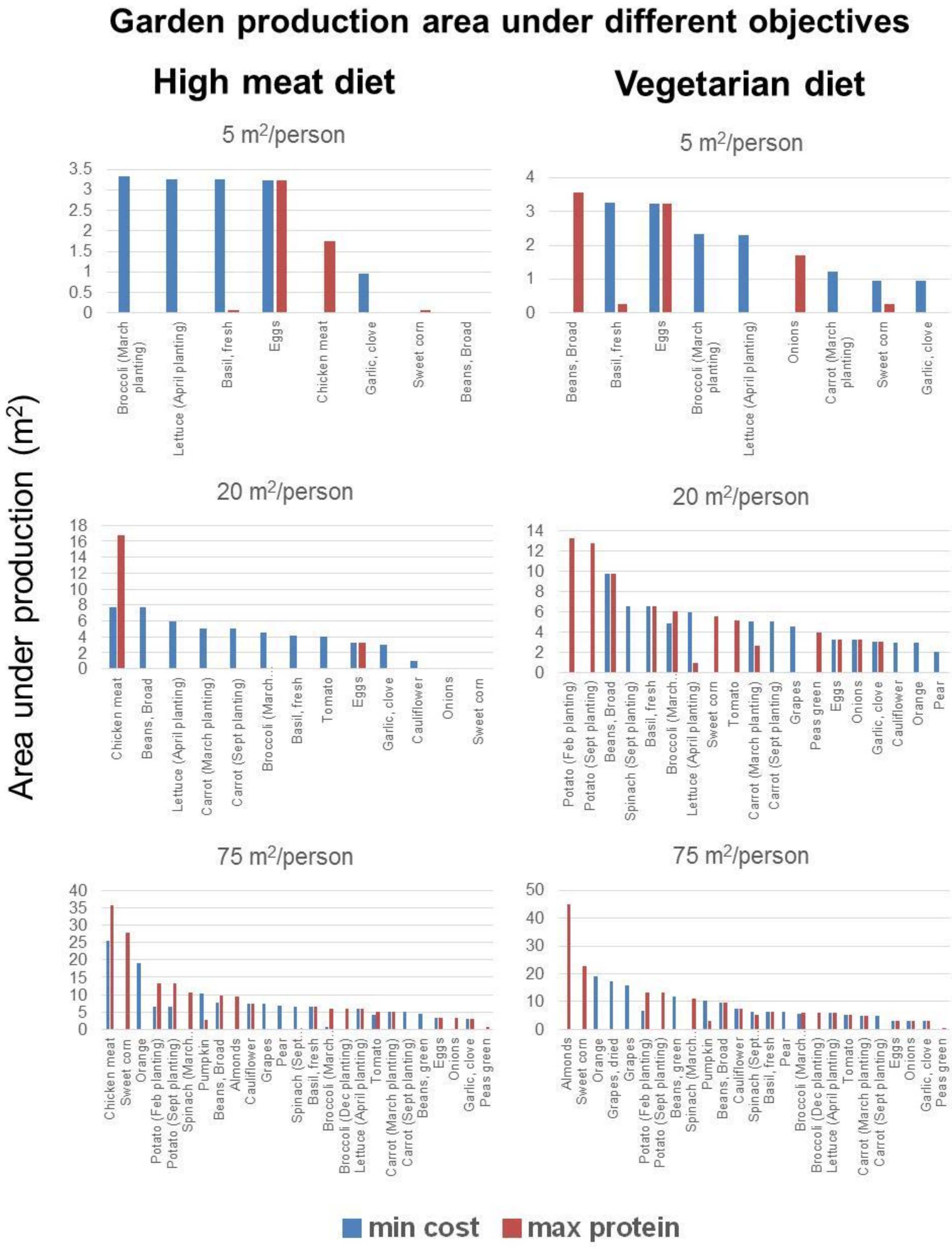


Figure 3 – Area under production for different items in small, medium and large gardens for each diet.

Key findings

In addition to the explicit results stated above, the modelling has shown us that dietary cost and UA are amenable to investigation via an optimisation approach such as LP. Moreover, such an approach allows us to simulate the "best case" intervention scenario, and helps us to ground optimistic claims regarding the direct benefits of UA. In the context of the case study here, the potential impact of UA can be seen to be modest (but not trivial). On the other hand, the potential impact of dietary change – specifically reduction in meat consumption – on reducing food costs is shown to be greater than the realistic contribution from UA. One of the key aspects of the modelling approach presented here is that the food items contributed by UA are considered within a complete dietary optimisation. This is important in the context of cost minimisation, as the model does not merely search for the highest net value items for UA, but rather for items that are able to displace more costly items in the diet (while still satisfying overall nutritional requirements).

For the theoretical results of this study to be translated into real outcomes, a number of practical challenges must be addressed. These include assessing the cost, and then arranging the financing, of the installation of the garden and poultry enclosure, as well as ensuring ongoing labour investment is not so high as to undermine the financial savings offered by the garden. In addition, it must be noted that productive gardening requires substantial knowledge and skills to manage seasonal plantings, as well as specific culinary skills to cope with seasonal produce.

Extending the model

The LUDO framework is generic and lends itself to a variety of extensions. One of the most obvious extensions would be to increase the number of zones (x) from the simple set of two (UA and external) presented in the current paper. Analyses on urban food security and threats to resilience would, for instance, benefit from the addition of at least a third intermediate zone representing peri-urban agricultural production.

Increasing the number of zones could open up the possibility of studying "food miles" in detail and optimising the food production system to minimise transport fuel. Large-scale farming operations in distant rural areas may permit the use of larger, more fuel-efficient forms of freight than smaller operations in peri-urban areas, so each food item i produced in zone x would need to be assigned both a distance and a transport mode (with associated fuel consumption) to determine fuel usage. Figure 4 shows an idealised conceptual model, with only four items (i = 1 to 4) spread across three basic zones (x = 1 to 3).

In the conceptual model, the generic items poultry, fruit and vegetables (i = 1, 2 and 3) are all available either in the UA zone or the local peri-urban zone. Meanwhile, cereals (i =4) are only available from the remote import zone. Fruit and poultry are available in all three zones in this conceptualisation. The diagram shows how optimisation could explore the trade-offs between constrained space (UA zone), inefficient transport (peri-urban zone) and long distance (remote import zone). The model would then determine where best to situate various forms of production. Such an analysis would still be constrained by other factors such as dietary intake and acceptable food cost, and particular forms of farming could be excluded from individual zones (e.g. in Figure 4, cereals are only available for production in the remote import zone, and vegetables are only produced in the UA and peri-urban zones).

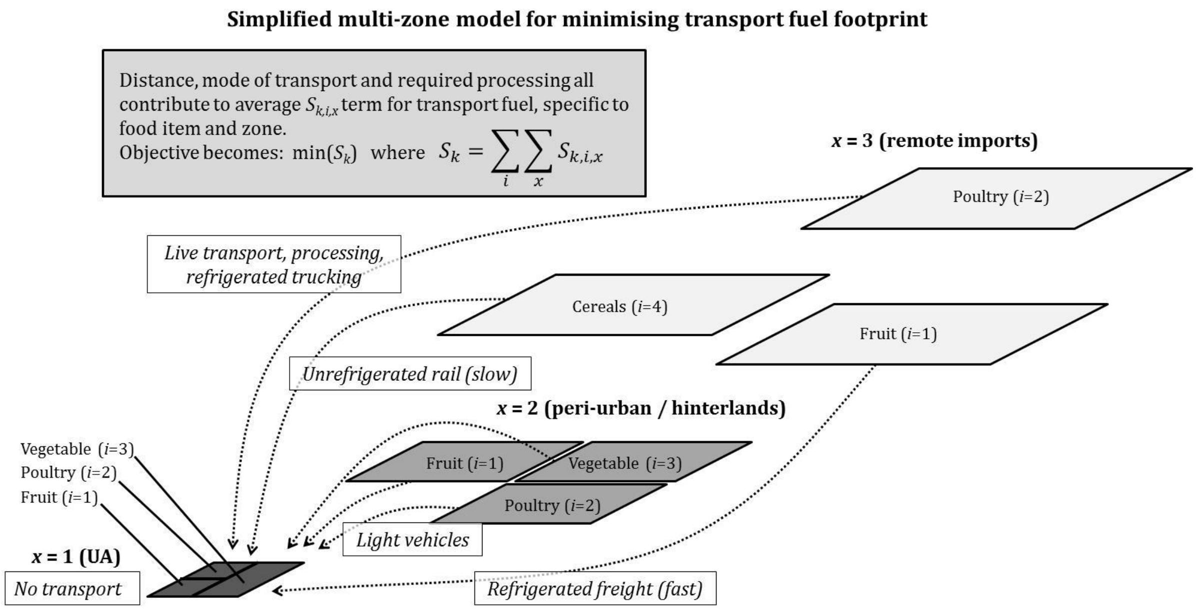


Figure 4 – A model of four food items grown across three zones, demonstrating how one might approach optimisation with the goal of minimising the transport fuel footprint of food.

While Ward *et al.* (2014a) included wild fish in the hypothetical diet, there is the potential to augment this with farmed fish. Aquaculture is one of the fastest-growing food production sectors in the world, and human consumption of farmed fish is now approximately equal to that of wild fish (FAO, 2014). Aquaculture could be readily considered in LUDO by adding $Y_{i,x}$ and $R_{k,i,x}$ terms to account for yield and resource inputs respectively of different farmed fish products. Resource inputs would need to include blue water, electricity (for semi-intensive ponds and intensive recirculating systems, which require aeration and pumping, and in some cases, heating or cooling of the water) and fishmeal, which is the major protein source in aquaculture feeds. Fishmeal replacement with vegetable-based protein could also be simulated, in the same way that poultry feeds are accounted for with an indirect footprint. Per-capita resource constraints could be applied to fishmeal based on limits to wild fish catch, to explore the potential for sustainable substitution of meat with farmed fish and trade-offs with land use when shifting to lower fishmeal aquaculture feeds.

The analysis presented in this paper assumed (implicitly) a steady-state. However, useful extensions to the LUDO model could involve testing different transient disruption scenarios or shocks, such as price spikes (either a spike in retail food prices, or a spike in the price of an input resource such as water), or constraining availability of particular products to simulate, for instance, closure of supermarkets. It would be useful to use LUDO to determine the optimal mix of UA items that mitigates against one scenario, and compare against the mix that best mitigates a different scenario (including business as usual), in order to possibly find universally high-performing crops or livestock that make sense across a range of scenarios.

More abstract extensions to the model could involve the inclusion of food storage (e.g. drying, preserving, curing or simply freezing) and an exploration of strategies that most effectively mitigate against short-term shocks – such as major storms or outbreaks of disease – that cause acute disruption to food supply chains. In this case, the model would be extended into a kind of "inventory analysis" linking the residence time of food items to their consumption rates, while meeting balanced dietary criteria. In a similar manner, the model could be adapted to account for food waste, and to test the potential for better utilising food waste (either as human food, animal food, or recycled as compost to replace a portion of the fertiliser input) in order to further reduce food costs and improve resilience.

The most urgent improvement to be made to LUDO in the future is increasing the quality of the data. Yields, water and fertiliser use and retail prices are all subject to a high degree of variability and more accurate data are needed to truly determine the cost-effectiveness of UA as a strategy to improve resilience. Prior to the search for better data, a sensitivity analysis can be conducted to determine the priority areas for refinement (i.e. a screening tool to identify the parameters that are most critical to the model results). Ultimately, better data on yield and cost efficiency will also allow the model to explicitly test the usefulness of particular production systems that are at the centre of some optimistic visions of UA, such as rooftop hydroponics, aquaponics, and intensive market gardening.

Further extensions to LUDO can be envisaged, that place quantitative values (to be minimised, maximised or constrained) on factors such as overall energy inputs, soil quality, and rainwater catchment. In this way, it may be possible to utilise the optimisation framework to assess the potential performance of innovative methods such as Permaculture (Mollison and Holmgren, 1978) that seek to minimise energy inputs in preparation for a post- fossil fuel era.

Conclusions

On the one hand, a major advantage of the LP method is that it forces a concrete, quantitative approach to analysis. On the other hand, a general lack of high-quality data on urban food production tends to weaken the quantitative approach. The analysis presented in this paper has drawn on relatively conservative assumptions such as applying national average yield to UA.

The constraints applied in LP allow us to force the UA production regime to conform to a realistic diet, rather than delivering overly optimistic results based on production of high-value niche crops. Subject to these constraints, optimisation yields a best-case estimate of the outcome, so can be seen to provide a “cautiously optimistic” approach to UA.

The model results in this paper suggest that a typical high meat consumer could perhaps reduce their food cost by approximately 10% if they undertook substantial home food operation including intensive poultry rearing for meat. The model predicts that a shift in diet towards vegetarianism would deliver twice the saving (around 20%), with a further 10% cost saving achievable through UA. In the context of resilience (to financial shocks), the results suggest that households could save a modest amount of money through dietary change and growing some of their own food.

The optimisation framework discussed in this paper represents a quantitative framework that is suitable for a variety of extensions to help ground claims being made around UA and local food production. We suggest further work to develop the model into multiple zones and account for distance and transport mode, which would facilitate optimisation to minimise the fuel footprint of urban food. A number of other extensions are possible, including more specialised scenarios to study the mitigation of short- and long-term food supply disruptions. Above all, the model can be improved by populating the database with more accurate data on yield, water and fertiliser inputs.

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