Small-scale urban agriculture results in high yields but requires judicious management of inputs to achieve sustainability

Robert McDougall[a,1], Paul Kristiansen[a], and Romina Rader[a]

[a]School of Environmental and Rural Sciences, University of New England, Armidale, NSW 2351, Australia

Edited by Alice Hovorka, Queens University, Kingston, ON, Canada, and accepted by Editorial Board Member Susan Hanson November 8, 2018 (received for review June 6, 2018)

A major challenge of the 21st century is to produce more food for a growing population without increasing humanity's agricultural footprint. Urban food production may help to solve this challenge; however, little research has examined the productivity of urban farming systems. We investigated inputs and produce yields over a 1-y period in 13 small-scale organic farms and gardens in Sydney, Australia. We found mean yields to be 5.94 kg·m^{-2}, around twice the yield of typical Australian commercial vegetable farms. While these systems used land efficiently, economic and emergy (embodied energy) analyses showed they were relatively inefficient in their use of material and labor resources. Benefit-to-cost ratios demonstrated that, on average, the gardens ran at a financial loss and emergy transformity was one to three orders of magnitude greater than many conventional rural farms. Only 14.66% of all inputs were considered "renewable," resulting in a moderate mean environmental loading ratio (ELR) of 5.82, a value within the range of many conventional farming systems. However, when all nonrenewable inputs capable of being substituted with local renewable inputs were replaced in a hypothetical scenario, the ELR improved markedly to 1.32. These results show that urban agriculture can be highly productive; however, this productivity comes with many trade-offs, and care must be taken to ensure its sustainability.

urban farming | productivity | food security | food production | emergy

One of the most pressing challenges of the 21st century will be to feed a projected global population of nine billion people while reducing humanity's agricultural footprint at the same time (1). Land clearing and more intensive use of existing croplands are often considered to be the two main options to increase crop production, yet biodiversity loss and increased greenhouse gas emissions are associated with both of these approaches (2–5). Urban agriculture (UA), the growing of crops within cities for human consumption, could be one means of increasing global food supply without relying on further land clearing (6), utilizing already cleared urban land and possibly allowing for "land sparing" in more natural rural areas (7).

UA's ability to address a portion of global food demand shows some promise, given that studies have demonstrated it can often produce yields of fruit and vegetable crops per square meter higher than on rural farms (e.g., refs. 8–11). A number of authors have attempted to estimate the proportion of total global provisioning provided by UA, with one commonly cited figure claiming it produces 15–20% of the world's total food supply (12); however, other authors consider that figure to be a substantial overestimation (13).

While UA has shown some potential with regard to improving food security and dietary diversity within developing countries (14–17), most research on UA in developed countries has focused primarily on its social, rather than productive values, with such research often reporting a range of positive social outcomes (18). UA in developed countries has also been found to be effective at producing high-value perishable crops, such as vegetables, in close proximity to where they will ultimately be consumed (16) and can provide important nutrients in low-income "food desert" areas, where geographic and economic factors can make fresh, healthy food difficult to access (17).

However, the existing literature suffers from several shortcomings that make it difficult to accurately determine the viability of UA as a provisioning strategy beyond these narrow areas, particularly within developed countries. For example, few studies that provide yield figures from UA incorporate data on the inputs used to achieve those outputs, leaving uncertain what trade-offs in terms of materials and labor may have been required to achieve the high yields often reported. With UA growing in popularity throughout the developed world (17, 19), it is essential that detailed analyses be undertaken into the costs and productive benefits of UA in these countries.

Of the few studies that have assessed inputs and outputs in UA, most have focused on a single indicator of value, such as economic (20, 21) or emergetic balance (10, 22). Economic analysis is useful as financial values reflect the worth that materials and services have to human society; however, such analyses often fail to capture the value of environmental services and disservices (23). Emergy (embodied energy) analysis has the advantage of being able to account for all inputs into a system, including those without a direct financial cost, by quantifying all materials and services in the form of a single metric relevant to

Significance

Growing food in cities for human consumption could be one means of increasing global food supply in the face of rising population growth and global food security concerns. While previous studies have shown that urban agricultural systems are productive, few studies provide yield figures that incorporate data on the inputs used to achieve the outputs. Across 13 urban community gardens, we show that yields were nearly twice the yield of typical Australian commercial vegetable farms. However, economic and emergy (embodied energy) analyses indicated they were relatively inefficient in their use of material and labor resources. Balancing the sustainability of urban food production with the cost of inputs is important to determine the trade-offs required to achieve high yields.

Author contributions: R.M., P.K., and R.R. designed research; R.M. performed research; R.M. analyzed data; and R.M., P.K., and R.R. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. A.H. is a guest editor invited by the Editorial Board.

[1]To whom correspondence should be addressed. Email: robert.n.mcdougall@gmail.com.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1809707115/-/DCSupplemental.

Published online December 24, 2018.

AGRICULTURAL SCIENCES

SUSTAINABILITY SCIENCE

virtually all parts of the geobiosphere: embodied solar energy, measured in solar emjoules (24).

To adequately assess the costs and provisioning benefits of UA in developed countries, we need to combine both economic and emergetic analyses to understand if UA has the potential to produce food efficiently and sustainably. Use of these complimentary forms of measurement will enable a more complete understanding of UA's potential role in addressing food availability concerns, examining its economic and environmental efficiency, and determining if it can have a valuable provisioning role.

To answer the following questions, we assessed 13 UA gardens in and around Sydney, Australia:

i) How do UA yields compare with those obtained from commercial (rural) farming systems?
ii) Does UA use material and labor resources efficiently?
iii) Under what conditions are UA systems sustainable?

Methods

Study Area. The study was carried out from November 2015 to May 2017 in the adjacent cities of Sydney and Wollongong, New South Wales, Australia; further details are provided in *SI Appendix*, section S1. All study sites were in urban locations, which were defined as those within 1 km of a regular contiguous area of at least 1 km^2 within which >50% of land was covered by built-up surfaces (16).

Gardening Logbooks. To determine the productivity of urban gardens, 13 gardeners working within urban areas of Sydney and Wollongong kept log books of their gardening activities over the course of a year. Details of gardener recruitment and recording techniques are outlined in *SI Appendix*, sections S2 and S3. Plots managed were typically small, with a median area of 10.8 m^2.

All research involving human subjects was approved by the University of New England Human Research Ethics Committee (approval no. HE15-196). All participants were given a written outline of the research being undertaken and had the opportunity to ask questions of the researchers before deciding to participate, and those who chose to proceed provided informed consent in writing.

Gardener Surveys. At the beginning of the study, all participants were surveyed about their gardening practices, experiences, and motivations (*SI Appendix*, section S4). As well as being used to compare input and output with gardener characteristics, the answers to these survey questions were used, along with observations of the garden, to assign that gardener a rating on a "permaculture index," modified from a study by Guitart et al. (25) (*SI Appendix*, section S5).

Economic Analysis. Economic values were determined by calculating the financial value of all inputs to and outputs from the farming systems. Financial values of materials and produce were determined by averaging the prices charged for those items in shops serving the Sydney area in July 2017. Values for organic produce were used where these varied from those for conventional produce. All values were gathered and analyzed as Australian dollars ($AUD) before being converted to US dollars ($USD) for presentation using the conversion rate for July 2017 of $AUD1.26 to $USD1.00. All labor was valued at $USD18.14 per hour, the minimum wage for a casual farmhand in Australia in July 2017 (26).

The benefit-to-cost ratio for each plot was determined by dividing the value of outputs by the value of inputs. Total input costs were also divided by kilograms of produce harvested to determine mean cost per kilogram.

Emergy Analysis. At the most basic level, agriculture is an energy conversion process, and is therefore an ideal system to study using emergy analysis, which examines energy flows throughout a system to understand their efficiency and sustainability.

Emergy analysis assesses all inputs and outputs to and from a system based on a single metric relevant to virtually all parts of the Earth's geobiosphere: solar energy (24). Any material or service can be assigned an emergy value, measured in joules of solar energy (sej), based on the amount of energy directly and indirectly required to produce it. The amount of emergy per unit of the product (e.g., $sej \cdot J^{-1}$ for fuel or food, $sej \cdot kg^{-1}$ for other materials) is referred to as its transformity and is a measure of the ease or efficiency with which it was produced, with lower values indicating simpler or more efficiently produced products.

Along with assessments of efficiency, emergy analysis allows determinations to be made about the sustainability of a system, based on the sources of the various inputs into that system (27) (Table 1 and *SI Appendix*, sections S6–S8).

Emergy values were obtained from the emergy literature for all materials used in gardening, along with values for labor and natural inputs into the system, with values and sources cited in *SI Appendix*, section S9. These were used to convert the units of inputs provided by gardeners into emergy values. In cases where estimates of a particular input's emergy were not available, the input's financial value was multiplied by the emergy value of $AUD1 to determine its emergy value. The emergy per dollar figure was obtained by using calculations for the emergy transformity of the entire Australian economy by the Center for Environmental Policy (28) National Environmental Accounting Database for the year 2008 and adjusting for inflation from 2008 to 2017. Final emergy values are based on the 2016 Global Emergy Baseline of 12E + 24 sej per year (29).

Input values were summed to determine the emergy used in each plot and then divided by the energy content of crops harvested to produce a transformity value, measured in $sej \cdot J^{-1}$ (solar emjoules per joule of produce). Energy content of produce was determined using the Food Standards Australia New Zealand (30) AUSNUT 2011–2013 Food Nutrition Database, with a fractional multiplier applied to the harvested weights of crops with inedible portions (e.g., peel) to reflect that not every part of the crop was fit for consumption.

Inputs into the systems were divided into the categories of indigenous, materials, and services following the conventions of emergy literature (*SI Appendix*, section S7). Superimposed on these categories, inputs were also designated as either renewable or nonrenewable (Table 1 and *SI Appendix*, section S6), and nonrenewable inputs were further classified as substitutable or nonsubstitutable, based on whether or not they could be replaced by a renewable substance that performed a similar function. Labor is considered partially renewable and partially nonrenewable proportional to the economy of the nation in which it is carried out as labor is supported by that economy (31). In Australia, labor is considered only 14.6% renewable (*SI Appendix*, sections S6 and S7).

Two emergy indices, the emergy yield ratio (EYR) and environmental loading ratio (ELR), were calculated for each site (*SI Appendix*, section S8). ELR values were calculated using both the actual reported data and for a hypothetical scenario in which all substitutable inputs were replaced with renewable inputs: the "maximum substitution" scenario.

Statistical Analysis. Statistical tests were carried out to assess possible relationships between garden production figures and a range of gardener traits and practices (*SI Appendix*, section S10) using R version 3.4.4 software (32). Dependent variables were yield per square meter, yield per hour of labor, emergy transformity, and benefit-to-cost ratio. Dependent variables were checked for normality and transformed as required before analysis to improve fit in a normal distribution.

Each dependent variable was modeled against each combination of three or fewer potential explanatory variables and a null model (with a constant in place of an explanatory variable) using linear models, and each model was ranked using a variation on the Akaike information criterion adjusted for small sample size (AIC_c) (33). Lower AIC_c values indicate a more highly ranked model. Models containing more than three variables were not used so as to avoid possible overfitting.

Akaike weight (W_i) was also calculated for each model to determine the probability that any given model was the best model to explain that particular variable (34). A 95% confidence set of models was constructed by summing the W_i values of models, starting with the highest ranked and progressing sequentially downward, until a cumulative W_i value of 0.95 was reached.

An *F* test was performed for the highest ranking model for each dependent variable and all other models with a ΔAIC_c value <2 with respect to that model to determine whether the model had significant explanatory power and the proportion of variability explained by it.

Results

Garden Yields. Produce harvested included 62 different varieties of vegetables, fruit, and herbs. Plots produced a mean output of 5.94 kg of crops per square meter with a large range from 1.99 to 15.53 $kg \cdot m^{-2}$. Yield per unit of labor was relatively low, with a mean figure of 1.29 $kg \cdot h^{-1}$ and a range of 0.21–2.28 $kg \cdot h^{-1}$.

Table 1. Summary of emergy terminology

Term	Definition
Emergy	A contraction of "embodied energy," emergy is a measure of how much energy was directly and indirectly required to produce an object or allow a process to occur, a measure of the energy consumed in its supply chain. As virtually all processes on the earth are ultimately powered by solar radiation, joules of solar energy required (solar emjoules) is used as a common unit, allowing the emergy of any material or process to be compared with any other.
Transformity	The amount of emergy required to produce one unit of an energy, material, or process, typically measured in sej·unit^{-1} (e.g., sej·J^{-1}, sej·kg^{-1}). Comparing the transformities of similar materials or processes can indicate which is the most efficient or simple, with a lower transformity indicating less energy was consumed in the supply chain for that material or process.
Renewable/ nonrenewable	In emergy analysis, an input is considered renewable if it meets one of two criteria: (*i*) It is provided freely by the natural environment, and its use does not have an impact on its future availability; or (*ii*) its rate of use does not exceed its rate of replacement (62). An example of a renewable input in this study that meets the first criterion is rainwater, as this falls on a surface regardless of whether or not it is captured and utilized, while an example of an input that meets the second criterion is homemade compost, as the rate of production of organic waste in Australian cities currently exceeds the rate at which it is used (63). Inputs that do not meet either of these criteria are considered nonrenewable.

Gardeners invested an average of 6.0 h of labor into each square meter of plot.

Yield per hour was best explained by labor per square meter (adjusted r^2 = 0.4924, P = 0.006589, negative relationship; *SI Appendix*, section S11) Seven models were required to achieve a 95% confidence interval; however, five of these contained labor per square meter as an explanatory variable (*SI Appendix*, section S11).

The predictive power of models examining yield per square meter was poor, with the highest ranked model being the null model and no models being statistically significant (*SI Appendix*, section S12).

Economic analysis. The mean financial value of inputs per kilogram of produce harvested was $USD28.53. This figure exceeded the average cost of per kilogram of purchasing the product at local stores for 53 of the 62 varieties of produce harvested (*SI Appendix*, section S13). Overall, gardening achieved low rates of return, with the mean value of materials and labor invested exceeding the value of yielded produce, resulting in a mean benefit-to-cost ratio of 0.62.

The benefit-to-cost ratio was poorly explained by the models tested, with the highest ranked model being the null model and no models being statistically significant (*SI Appendix*, section S14).

Emergy analysis. Emergy analysis showed that the mean emergy expended to produce 1 J of edible produce (the produce transformity) was 3.16E + 7 sej. Transformity was best explained by labor per square meter (adjusted r^2 = 0.2738 P = 0.04667, positive relationship; *SI Appendix*, section S15).

Renewable materials made up a mean 10.28% of total inputs across sites, with nonrenewable materials, labor, and indigenous inputs making up 60.28%, 29.34%, and 0.09% of input emergy, respectively (*SI Appendix*, section S16). The total renewable fraction of all inputs was 14.66% once indigenous inputs and the renewable portion of labor inputs were included, resulting in a mean ELR of 5.82. Under the maximum substitution scenario, renewable materials made up 38.65% of inputs, with a total renewable fraction of 43.03%, resulting in a much lower ELR of 1.32.

The low level of indigenous inputs resulted in the study sites having a mean EYR of 1.00, the lowest value possible within an agricultural context.

Garden Surveys. The majority of gardeners indicated that they were not highly motivated by the desire to produce large quantities of food. Of the nine reasons suggested during surveys as possible motivations for carrying out gardening activities, the idea that gardening could reduce personal spending on food had the lowest mean rating on a scale from 1–5, with environmental, social, recreational, and personal health-related motivations all ranking more highly (Fig. 1).

Only one of the gardeners who completed the year of recording was a horticultural professional, with the rest having unrelated occupations. Despite this, many gardeners had a large amount of experience with gardening, with the mean and median number of years that the gardeners had been involved in the practice being 20.96 y and 20 y, respectively.

Discussion

The Productivity of UA. We found that the productivity of UA was high across the study sites and exceeded that of typical rural vegetable farms in Australia. Ten years of annual surveys of 11 commonly grown culinary vegetable crops on Australian commercial farms found that when averaged over that period, the combined mean yield of all 11 crops was just 54% of the level found in this study at 3.18 kg·m^{-2} (35) (Fig. 2). The difference between these figures is even more noteworthy when considering that organic production systems typically have lower yields, with yields from Australian organic farms averaging only 73% of those of their conventional counterparts (36), meaning that the systems covered in this study likely produced more than twice the average yield of typical Australian rural organic farms.

One of the reasons for the higher outputs reported here is likely due to the substitution of mechanical labor with mostly manual labor. Using manual labor allows for a higher cropping density than is possible in machine-managed systems (37). The use of manual labor also allows for different crops to be grown together, resulting in systems potentially "overyielding," where the sum of crop yields in a polyculture exceeds the yield that any one of those crops growing alone would be able to produce (38).

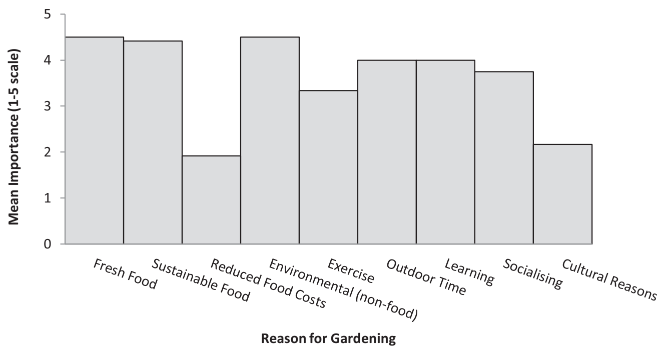

Fig. 1. Mean motivations for engagement in UA listed by volunteers in surveys.

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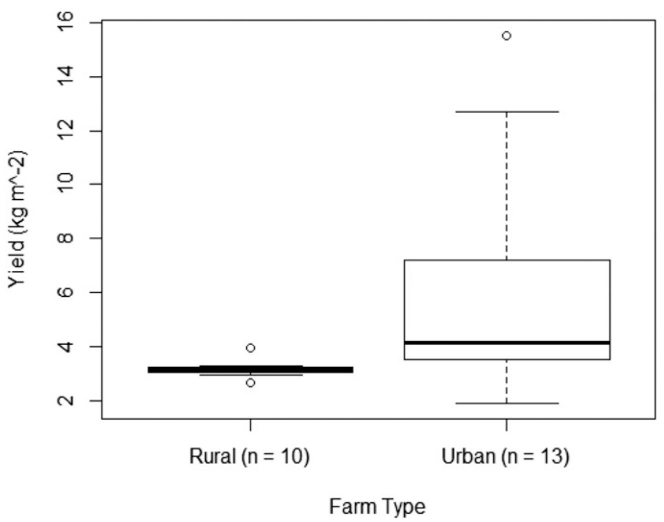

Fig. 2. Comparison of typical rural commercial vegetable yields with urban farm yields found in this study. Each data point for rural yields represents a mean Australia-wide figure for a single year (2005–2015), while each data point for urban yields represents a year's worth of production from a single plot examined in this study.

This mean yield figure is close to the mean of 6.19 $kg \cdot m^{-2}$ reported in 15 other studies from around the world that have carried out primary analyses of the output of UA systems (*SI Appendix*, section S17). Despite the high performance in terms of output per unit of land, the studied systems were of low efficiency in terms of their use of material and labor resources, as shown by their poor emergy measures and benefit-to-cost ratios. The low EYR found here is similar to that reported in two previous emergy analyses of UA, with both Beck et al. (22) and Bergquist (10) finding natural inputs made only a very small contribution to total inputs, being overwhelmed by anthropogenic inputs by three orders of magnitude. This implies that, in general, rather than capturing free environmental emergy, UA systems mostly convert emergy already under human control from one form to another.

The mean transformity reported here (3.16E + 7 $sej \cdot J^{-1}$) is higher than in any published studies of fruit and vegetable cropping that we examined (*SI Appendix*, section S18). Beck et al. (22) and Bergquist (10) found transformities in their studied urban systems to be close to an order of magnitude less than the mean values found in this study, and the values reported by those authors are themselves in the higher range of values typically reported for rural systems, with most transformities for fruit and vegetable crops being in the range of 10E + 4–10E + 6 $sej \cdot J^{-1}$ (39–43) (*SI Appendix*, section S18).

However, all previous emergy studies of agricultural systems that we are aware of examined work carried out either by professional farmers or researchers, not amateur gardeners as in this study, and this may partly explain the poor emergy results. The input of labor per square meter recorded here is higher than in all but one of the five studies listed in *SI Appendix*, section S17 that recorded this metric, and the finding of a significant negative relationship between yield per hour of labor and labor per square meter implies that the gardeners may have worked relatively inefficiently, with additional labor not resulting in a proportional increase in productivity (44). This is also consistent with the finding of a positive relationship between transformity and labor per square meter; increasing labor, by definition, increases inputs, and thus leads to an increase in transformity if not accompanied by a corresponding increase in outputs (24).

While the subject gardeners were generally highly experienced, they were motivated more by recreational than productive goals (Fig. 1), which may mean that their work was carried out at a low intensity. Vogl et al. (45) reported that amateur gardeners working plots in the same allotment garden as the authors invested an average of 1.7- to 2.8-fold more hours into their plots than the authors did and spent some of their "gardening" time engaged in nonproductive leisure activities. The gardeners examined in this study may have worked in a similar fashion.

The same reasoning may also explain the poor economic outcomes found in this study. While the economic value of inputs exceeded the economic value of outputs on average, it may be reasonable to exclude labor costs in this analysis, given the motivations of gardeners. When only material costs were included in the benefit-to-cost analysis, the mean ratio improved from 0.62 to 2.81, indicating that gardens produced a favorable return on the costs of material inputs invested.

The Sustainability of UA. Despite the survey results showing gardeners placed a high value on environmental sustainability (Fig. 1), the reliance on nonrenewable materials was high, leading to a moderate mean ELR value of 5.82. ELR values below 2 are generally considered "sustainable," while those above 10 are generally considered unsustainable (27), with a value of 5.82 placing the studied plots within the middle of the range of a wide variety of other fruit and vegetable production systems, both rural and urban and employing a range of production techniques (*SI Appendix*, section S19). However, under the maximum substitution scenario, the picture changes markedly, with the ELR improving to 1.32, a value within the low range of those for fruit and vegetable farms.

Convenience may be a factor explaining why gardeners relied so heavily on nonrenewable inputs (46). For example, while organic waste materials that could be used as a substitute for purchased compost, mulch, and imported soil form a major part of the domestic waste stream of cities throughout the world (47), the process of converting this into a useful resource takes time and effort. Composting requires a large receptacle and outdoor space to keep it, some degree of knowledge about effective composting practice, and a period of time from weeks to months to allow the composting process to take place. For urban residents who may be time-poor or not have a private outdoor space but who have easy access to many shops that sell cheap, commercially produced, bagged compost (mean price across three large chain outlets in Sydney in July 2017 was $USD0.21 per liter), the ease of purchasing may be seen to outweigh the environmental benefits that come with self-producing, despite gardeners' stated intentions.

A similar situation likely exists with other nonrenewable inputs, such as municipal water and purchased seeds and seedlings, where the personal cost and effort required by the individual gardener to obtain these from nonrenewable sources is lower, despite the overall impact on the environment being greater (48). Further, while the majority of the gardeners involved in this study had an aversion to using synthetic chemicals due to environmental concerns, they may have had less understanding of the issues surrounding the emergy of materials, which resulted in higher ELR values across study sites, as this knowledge is not widespread among the general public (49).

Along with adopting the maximum substitution scenario, the ELR of the plots could also potentially be improved by changing the way labor is assessed in this analysis. Given that gardening was primarily viewed as a recreational activity by gardeners, it may be reasonable to assume that the time and emergy "cost" it represents would be expended anyway on other, nonproductive, recreational activities if the gardeners did not participate in gardening (50). If this assumption is used, it may be appropriate to treat labor as a 100% renewable input rather than a mostly nonrenewable one.

If the assumption that labor is entirely renewable is used in conjunction with the maximum substitution scenario, then the mean ELR improves even further to 0.47, a figure among the lowest found in the emergy literature for vegetable and fruit production (*SI Appendix*, section S19). While this very low ELR value represents a best-case scenario that may, in reality, not be fully achievable due to trade-offs (e.g., more labor may be required to obtain renewable inputs), it shows that there is substantial room to improve UA practice so that it becomes a highly sustainable activity.

Our findings that UA can potentially be highly sustainable from an emergy perspective are in general agreement with studies that have assessed the sustainability of UA via other means. Life cycle analyses have shown that UA can have environmental benefits, reducing greenhouse gas emissions through reduced energy use in transport and storage of food, reduced entry of run-off water and organic waste into the waste stream, reduced energy for lawn maintenance, and improved carbon sequestration (51, 52). UA also has the potential to improve urban biodiversity through replacing low-diversity vegetation, such as lawns, with more diverse garden plantings, which can, in turn, provide habitat and resources for urban biota, including ecologically important groups, such as pollinators (53, 54). However, not all findings on the environmental impact of UA have been positive, with it sometimes being associated with excessive application of pesticides, fertilizers, or manures, posing a risk to local insect fauna and water quality (55), or increased mosquito breeding due to irrigation (e.g., ref. 56).

Implications for the Future of UA. This study has shown that UA can be a highly productive use of land, with each square meter put under cultivation equivalent to nearly twice that area of rural farmland and potentially creating the possibility of land sparing (7). Beyond the ongoing inputs required to carry out farming activity (e.g., labor, materials), UA comes at very little opportunity cost as it can be used as a way of obtaining productive value from land that would otherwise not be put to effective use (38).

While the inputs required for UA appear to be high and, in many cases, not sustainable, both of these issues could be mitigated through more judicious sourcing of materials like water and organic matter. These resources are relatively abundant in most urban environments and are often underutilized to the point that they are treated as waste (57, 58). The low ELR figures that could be achieved through such alternative sourcing means that some of the poorly performing figures can be viewed from a different perspective. While the low EYR recorded shows the systems relied heavily on anthropogenic inputs, if those inputs were mostly waste products that had no other use, or would create a disposal burden if not used in UA, then these systems could still be viable. The same is true for the high transformity value; while the total emergy inputs were large, if most of those inputs were otherwise valueless materials or labor that gardeners undertook for recreational purposes, then high transformity figures do not necessarily indicate inefficient performance.

The fact that gardeners are prepared to invest their time in working on UA projects motivated by social, recreational, and environmental goals over productive ones also suggests that expanding UA beyond private spaces and controlled public spaces (e.g., community gardens) and into uncontrolled public spaces, such as road verges and park margins, may be viable (e.g., refs. 59–61). However, the relative inefficiency of labor found in this study, and the unsustainable economic situation encountered once a market price is attached to that labor, may ultimately restrict how productive UA can be overall.

In conclusion, while the land available for UA may be limited, the productivity of that land can be high. Future research should examine the economic issues encountered with labor in this study and investigate ways to increase the usage of recycled materials in UA to improve the sustainability of those systems. If performed correctly, the practice can be carried out with very low environmental impact and cost, and there would thus be few disadvantages in promoting an expansion of UA.

ACKNOWLEDGMENTS. We thank Daniel Campbell for providing advice on emergy analysis. R.M. was funded by an Australian Postgraduate Award scholarship and a University of New England Completion Scholarship.

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