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Urban Agroecology: designing biodiverse, productive and resilient city farms

Agroecología urbana: diseño de granjas urbanas ricas en biodiversidad, productivas y resilientes

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ABSTRACT

Urban agriculture (UA) has been bolstered as a major sustainable alternative to enhance food security on an urbanized planet. Although it has been estimated that UA can provide 15–20% of global food, it is questionable weather UA can significantly contribute the level of food self-sufficiency of cities, due to low yields reached in most existing urban farms. Agroecology can help enhance the productive potential of UA by providing key principles for the design of diversified, productive, and resilient urban farms. Herein we describe the principles and practices used in the redesign of urban agriculture featuring: (a) increasing soil quality via enhancement of soil organic matter content and biological activity that lead to protection against pathogens and efficient use of soil nutrients and water and (b) enhancement of plant health through biological control and plant productivity via optimal planning of crop sequences and combinations.

RESUMEN

La agricultura urbana (AU) ha surgido como una importante alternativa sostenible para mejorar la seguridad alimentaria en un planeta urbanizado. Si bien se ha estimado que la AU puede proporcionar entre el 15 y el 20% de los alimentos a nivel mundial, se cuestiona si acaso la AU puede contribuir significativamente al nivel de autosuficiencia alimentaria de las ciudades, debido a los bajos rendimientos alcanzados en la mayoría de las granjas urbanas existentes. La agroecología puede ayudar a mejorar el potencial productivo de la AU al proporcionar principios claves para el diseño de granjas urbanas diversificadas, productivas y resilientes. Aquí describimos los principios y las prácticas utilizadas en el rediseño de la agricultura urbana mediante: (a) aumento de la calidad del suelo a través de la mejora del contenido de materia orgánica y la actividad biológica que conduce a la protección contra patógenos y al uso eficiente de los nutrientes y el agua del suelo y (b) mejora de la sanidad vegetal a través del control biológico y la productividad vegetal a través de la planificación óptima de secuencias de cultivos y combinaciones.

Palabras clave: Agroecología, agricultura urbana, calidad del suelo, control biológico.

INTRODUCTION

By 2030, 60% of the world's urban population will live in cities, including 56% of the world's poor and 20% of the undernourished (De Bon *et al.,* 2010). Today, for a city with 10 million people or more, over 6,000 tons of food has to be imported every day, traveling an average of 1,000 miles (De Zeeuw *et al.,* 2011). A significant rise in food prices, if not food shortages can be expected with compounding factors such as failures in industrial agriculture, increased energy costs and demographic pressure, and as multinational corporations increase their control of the food system (Holt-Gimenez, 2017).

Given this grim scenario, urban agriculture (UA) has been bolstered as a major sustainable alternative to enhance food security on an urbanized planet. Production of fresh fruits, vegetables, and some animal products, within cities can improve local food security and nutrition of consumers, especially in underserved communities (Smit *et al.,* 2001). UA has spread rapidly. From 1950-2005 UA has expanded in developing countries by 3.6% annually and >30% in the past 30 years in the United States (Siegner *et al*., 2018). Although it has been estimated that UA can provide 15–20% of global food, an important question remains: what level of food self-sufficiency can cities realistically obtain through UA. A survey with the goal of providing

300 g day^{-1} per capita of fresh vegetables, found that 51 countries have insufficient urban area to meet the recommended nutritional target (Clinton *et al*., 2018). In addition, UA would require 30% of the total urban area to meet the global demand for vegetables, a space that may not be available due to land tenure issues and urban sprawl (Martellozzo *et al.,* 2014; Badami and Ramankutty, 2015). Other estimates suggest that self-sufficiency could be achieved, but this depends on how UA is designed and managed (i.e. farm designs, crop arrangements, production practices used, size of plots, etc.). Several studies estimate that UA may supply from 30-100% of city vegetable demand in various cities (Siegner *et al.,* 2018), but the question of how much of the urban produced food is actually being consumed by low-income food insecure communities is beyond the scope of this review. Our focus is to examine the production potential of urban agriculture when designed and managed using agroecological principles.

The majority of urban farmers lack ecological horticultural skills and do not always optimize crop density or diversity, most suffer pest losses and reach poor yields, thus modifications of existing cultural practices are needed to enhance soil quality, crop health and productivity. Agroecology can help realize the productive potential of UA by providing key principles for the design of diversified, productive, and resilient urban farms. Herein we describe such principles and their application to achieve the potential of UA.

THE MAGNITUDE AND SIGNIFICANCE OF URBAN AGRICULTURE

The United Nations Development Programme (UNDP) estimated that about 800 million urban dwellers are engaged in UA globally, producing 15 to 20% of the world's food. In the 1990s this number of people comprised 30% of the global urban population, 200 million of whom produced food for sale (Smit *et al.,* 2001).

In 1993, just 15% of food consumed in cities worldwide was grown in cities. However, by 2005, that proportion increased to 30%. In other words, urban food production doubled in just over 15 years (Martellozzo *et al.*, 2014). This expanding trend of urban agriculture continues today. Overall, global estimates of available space for UA ranges from 1–7 million hectares or 1.4%–11% of the urban area. Projected global production was estimated at 100-180 million tons of food per year (Clinton *et al.,* 2018).

Data from urban areas around the world indicate that a significant portion of the local vegetable and animal intake can be met locally. Studies have reported that urban agriculture provides as much as 90% of leafy vegetables in Dar es Salaam, Tanzania, as well as 76% of vegetables in Shanghai and 85% of vegetables in Beijing. It has been well documented that many African towns and cities produce much food in urban vegetable gardens which may include livestock such as cattle and poultry (Zezza and Tasciotti, 2010). For example 60% of milk sold in Dar es Salaam, Tanzania, comes from UA. Sixty-eight percent of all urban households in that country are involved in UA. Dakar produces 60% of the national vegetable consumption of Senegal whilst urban poultry production amounts to 65% of the national demand. In Hanoi, Viet Nam, 80% of fresh vegetables, 50% of pork, poultry and fresh water fish, as well as 40% of eggs, originate from urban and peri-urban areas. The urban and peri-urban areas of Shanghai produce 60% of the city's vegetables, 100% of the milk, 90% of the eggs, and 50% of the pork and poultry meat (van Veenhuizen and Danso, 2007; De Bon *et al*., 2010).

UA has been critical during times of crisis. During World War II, United States households produced enough to meet 40% of the nation's fresh vegetable demand during the "victory garden" movement. In Sarajevo, Bosnia and Herzegovina, 2 years after the blockade began in 1992, self-reliance in urban food production was estimated to have grown from 10% to over 40% for vegetables and small livestock (Brown and Jameton, 2000). During the "special period" right after the collapse of the Soviet bloc, over 26,000 popular gardens covered 2,439 ha in Havana, Cuba, producing 25,000 tons of food each year. Today UA and peri-urban agriculture produce about 50% of the fresh food of the island covering about 56,000 ha. More than 39,000 tons of meat, 787 litters of goat milk and 216 million eggs are produced in more than 300,000 urban farms and gardens. UA generates about 300,000 jobs, of which, 66,055 are taken by women, and 78,312 by young people (Funes and Vázquez, 2016). In Rosario, Argentina, thousands of families were able to feed themselves during the country's 2002 economic crisis by growing their own food. More than 800 community gardens proliferated in the city feeding some 40,000 people. Today Rosario has five large innovative parks covering a total of 72 ha of land. Horticulture is practiced on 24 ha of the total area where more than 600 gardeners grow vegetables for the market and home consumption (FAO, 2015).

PRODUCTIVITY OF URBAN FARMS

Assessments of the productivity potential of urban farms have been conducted in many US cities. In 2008, Philadelphia's 226 community and squatter gardens grew roughly 900,000 kg of midsummer vegetables and herbs worth $4.9 million US dollars (Kremer and DeLiberty, 2011). Running at full bore, Brooklyn's Added Value Farm, which occupies 1,11 ha, funnels around 18,000 kg of fruit and vegetables into the low-income neighborhood of Red Hook. In Camden, New Jersey, an extremely poor city of 80,000 people, community gardeners at 44 sites harvested almost 14,000 kg of vegetables, enough food during the growing season to feed 508 people three servings a day. In Detroit's vibrant communal and commercial farming community, which in 2014 produced nearly 181,000 kg of food — enough to feed more than 600 people — in its more than 1,300 community, market, family and school gardens (ENSIA, 2015).

Researchers have calculated that Cleveland, Ohio, with its population of 400,000 habitants, has the potential to meet 100% of urban dwellers need for fresh vegetables, 50% of poultry and eggs, and 100% of honey (Grewal and Grewal, 2012). Under average growing conditions in a 130 days growing season, a 10 x 10 m plot can provide a household's yearly vegetable needs, including much of the household's nutritional requirements for vitamins A, C, and B complex and iron (Siegner *et al*., 2018). One of the few studies estimating crop yields at the farm level (Grewal and Grewal, 2012) indicates that conventional urban gardening has the lowest yields (1.20–1.35 kg m^{-2} $year^{-1}$) and thereby the largest land requirements to meet people food needs, while intensive urban gardening reached levels of 6.20 kg m^{-2} $year^{-1}$ and thus, smaller land requirements. The latter study showed that the city of Cleveland should be able to achieve considerable levels of self-reliance in fresh vegetable, fresh fruit, shell eggs, poultry, and honey.

Most of the above data proceed from urban farms not necessarily managed with agroecological methods. When these methods are applied, productivity potential can increase considerably. For example, the Cleveland study shows that under conventional urban gardening the city would be able to attain 22% self-reliance in fresh produce, but more than 50% when using intensive organic gardening methods (Grewal and Grewal, 2012). In Cuba, agroecologically based "organopónicos" (intensive gardens) reach on average 15-20 kg m^{-2} $year^{-1}$ (Funes and Vázquez, 2016). During the 1984-1985 season in central Chile, Infante (1986) conducted an evaluation of an 11.05 m^2 vegetable garden containing 16 crops species displayed in complex rotations and mixtures produced 177,4 kg $year^{-1}$ or 16 kg m^{-2} $year^{-1}$ (Table 1). The secret of the high production potential of the Cuba and Chile examples is the application of agroecological principles to guide the intensive cultivation of a diversity of vegetables, roots and tubers, and herbs in relatively small spaces.

Following some of the designs and practices used in Cuba and Chile, a 100 m^2 diversified garden was established in Berkeley, California (Altieri, unpublished data). The garden contained a total of 492 plants belonging to 10 crop species grown in a mixed polycultural design. Total production reached a yield of 2.7 kg of edible green biomass per m^2 (a total of 270 kg in the whole plot) in a three month period (Table 2), close to the desired level of 10 kg m^{-2} per year.

AGROECOLOGICAL PRINCIPLES FOR URBAN FARM DESIGN

Agroecology has for decades been applied to improve small farming agriculture in the developing world (Altieri, 1995). The same well-established agroecological principles applied in rural areas for the design and management of diversified farms where external inputs are replaced by natural processes can be applied to urban farms. Agroecological principles (Table 3) are applied by way of various practices which lead to optimal recycling of nutrients and organic matter turnover for soil fertility, closed energy flows, water and soil conservation and enhanced pest regulation all key processes necessary to maintain UA productivity (Altieri, 1995).

Agroecological systems are not intensive in the use of capital, labor, or chemical inputs, but rather they improve the efficiency of biological processes such as photosynthesis, nitrogen fixation, solubilization of soil phosphorus, and the enhancement of biological activity above and below ground. The "inputs" of the system

Table 1. Productivity obtained in a 11.05 m^2 urban garden featuring 16 crop species in Central Chile (Infante, 1986).

Cuadro 1. Productividad obtenida en un jardín urbano de 11,50 m^2 con 16 especies de cultivo en Chile Central (Infante, 1986).

Crop	Production (kg m^{-2})	% Contribution to total production
Tomato	79.4	44.75
Chard	53.9	30.38
Fava beans	12.9	7.27
Onions	9.7	5.47
Cabbage	3.8	2.14
Lettuce (Summer)	2.9	1.63
Broccoli	2.5	1.41
Cilantro	2.4	1.35
Beets	2.4	1.35
Spinach	2.3	1.30
Radish (Winter)	1.4	0.79
Carrot	1.2	0.62
Radish (Summer)	1.1	0.62
Lettuce (Winter)	0.7	0.39
Peas	0.4	0.23
Brussel sprouts	0.4	0.23
Total Production	**177.4 kg**	**100%**

Table 2. Biomass production and nutrient output in a 100 m^2 urban garden in Berkeley, California (Altieri, unpublished data).
Cuadro 2. Producción de biomasa y salida de nutrientes en un jardín urbano de 100 m^2 en Berkeley, California (Altieri, datos no publicados).

Crop	# of plants Crop^{-1}	Edible biomass Plant^{-1} (g)	Edible biomass m^{-2} (g)	Edible biomass Yield (kg ha^{-1})	Calories m^{-2} (g)	Vit. A m^{-2} (g)	Vit. C m^{-2} (g)	Protein m^{-2} (g)	Protein ha^{-1} (kg ha^{-1})
Arugula	83	406	2030	20300	508	15663	305	52	524
Bokchoy	46	966	4828	48283	628	64714	2173	72	724
Chard	102	504	2519	25192	479	46222	756	45	453
Green Lettuce	68	425	2125	21250	319	47207	196	29	289
Red Lettuce	32	225	1125	11250	180	25286	42	15	150
Mizuna	65	1152	5762	57617	864	127995	530	78	784
Spinach	15	186	932	9317	214	20939	262	27	266
Kale	45	353	1767	17667	866	53000	2120	57	565
Pak-choi	36	217	1087	10867	217	54333	391	13	130
TOTAL	492	4435	2714	27137	4275	455360	6773	389	3886

Table 3. Agroecological principles for the design of biodiverse and productive urban farms.
Cuadro 3. Principios agroecologicos para el diseño de granjas urbanas biodiversas y productivas.

1.	Enhance the recycling of biomass, optimising organic matter decomposition and nutrient cycling.
2.	Enhance functional biodiversity – natural enemies, antagonists, soil biota, etc., by creating appropriate habitats.
3.	Provide the most favourable soil conditions for plant growth, by managing organic matter and by enhancing soil biological activity.
4.	Minimise losses of energy, water, nutrients and genetic resources via conservation of soil and water resources and agrobiodiversity.
5.	Diversify species and genetic resources at the field and landscape level.
6.	Enhance beneficial biological interactions among agrobiodiversity components promoting key ecological processes.

are the natural processes themselves; this is why agroecology is referred to as an "agriculture of processes" (Gliessman, 1998).

The integrity of a well-designed urban farm relies on synergies between plant diversity, beneficial insects and a soil rich in organic matter and biota. Such farms should exhibit lower pest populations due to an abundance of natural enemies and other mechanisms, as well as soils with high organic matter and active biologically thus, sponsoring good soil fertility and prevention of pathogen infection via antagonisms (Altieri and Nicholls, 2004). Integration of soil, water, and pest management practices constitute a robust pathway for optimizing soil quality, plant health, and crop production in urban farms.

THE PILLARS OF AGROECOLOGICAL URBAN FARMS

The redesign of urban agriculture arises from the application of agroecological principles (Nicholls *et al.,* 2016) that lead to: (a) increasing soil quality via enhancement of soil organic matter content and biological activity that lead to protection against pathogens and efficient use of soil nutrients and water, and (b) enhancement of plant health and productivity via optimal planning of crop sequences and combinations (Figure 1).

Enhancing soil quality

Addition of organic matter

Organic matter and its replenishment is a major component of soil health and management. Agroecology promotes a series of soil-health-improving management practices such as complex crop rotations, cover cropping, applications of compost and a variety of organic amendments (Nicholls *et al.*, 2016). These management practices, increase inputs of soil organic matter (SOM), decrease losses of carbon, maintain soil cover, and decrease soil disturbance, influencing diverse and crucial biological activities such as antagonisms, litter decomposition, nutrient mobilization, etc. Improved soil properties resulting from such practices have added benefits such as more available water, less compaction, enhanced nutrient availability, and the production of growth-promoting substances, which promote growth of healthy and productive plants (Magdoff and van Es, 2000).

After one or two seasons of applying agroecological practices, levels of nitrogen, phosphorus and potassium, pH, organic matter and some micronutrients often increase with time (Nicholls *et al.*, 2016). Biomass and abundance of earthworms also increases which in turn improves soil structure, and other beneficial microorganisms thrive, which decompose organic residues and mineralize nutrients (Cheeke *et al*., 2012). Mycorrhizal fungi and some antagonists that suppress many soil-borne diseases also increase with time. Due to the enhancement of soil chemical and biological parameters, most crops grown on compost-amended soils have a positive yield response (Abbot *et al*., 1995). Table 4 shows how yields of tomatoes vary depending

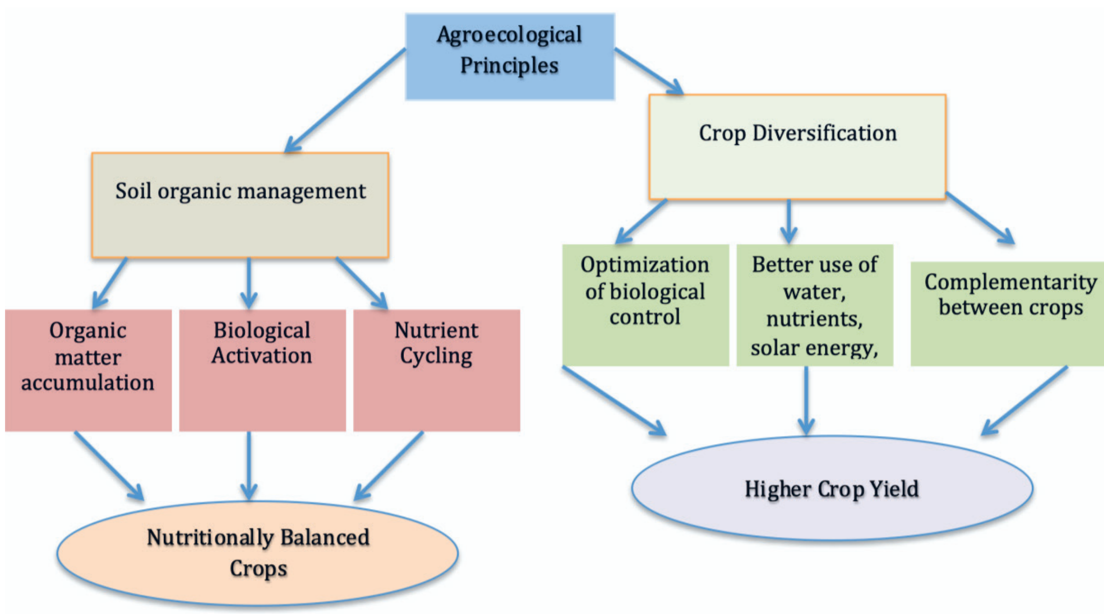

Figure 1. Agroecological principles for the re-design of organically rich soil, diversified and productive urban farms.

Figura 1. Principios agroecológicos para el rediseño de granjas urbanas ricas en suelos orgánicos, diversificadas y productivas.

Table 4. Yields of tomatoes (var. Principe Borghese) under various organic fertilization regimes (each treatment = N equivalent to 50 kg ha^{-1}) in urban farms in Berkeley, California (Altieri, unpublished data).

Cuadro 4. Rendimiento de tomates (var. Principe Borghese) bajo varios tratamientos de fertilizacion orgánica (cada tratamiento corresponde a un equivalente de N de 50 kg ha^{-1}) en una granja urbana en Berkeley, California (Altieri, datos no publicados).

Treatment	# Of fruits plant^{-1}	Average fruits weight (kg)	Yield plant^{-1} (kg)
No fertilization	10	0.016	0.16
Compost	34	0.021	0.73
Fish emulsion	40	0.018	0.70
Mycorrizhae enriched compost	27	0.019	0.54

on the applied organic fertilization treatments, where compost and fish emulsion had the biggest production effects in experiments conducted in an urban farm in Berkeley, California (Altieri, unpublished data).

A main challenge for urban farmers is to access animal manure as a source of nitrogen, as shortage of available nitrogen may greatly reduce crop yields. Many cities do not allow animal rearing, which further limits manure availability. As an alternative, many farmers grow green manures such as fava beans (*Vicia faba* L.), vetch (*Vicia atropurpurea* Desf.) and peas (*Pisum sativum* L.), or a mixture (at times adding 20% rye or barley) in fall and winter. This constitutes an inexpensive strategy to increase nitrogen supply for crops. In addition, cover crops can exhibit several multiple effects simultaneously including suppression of weeds, soil borne diseases and pests, protect the soil from rain and runoff, improve soil aggregate stability, add active organic matter and scavenge for nutrients (Clark, 2007).

In California, a vigorous green manure (i.e. fava beans or vetch) growing for four to six months before incorporation in early spring, typically adds between 112 and 224 kg N ha^{-1} to the soil for the succeeding crop (Clark, 2012). Yields of most vegetable crops increase with increasing rates of nitrogen. The C/N ratio of incorporated materials should be equal to or less than 20:1 to assure net short-term mineralization and avoid nitrogen "hunger" (Clark, 2012). Cover crop species vary in nitrogen content and mineralization rate after incorporation. Leguminous cover crops decompose and release nitrogen more rapidly than grass or cereal covers, and even the most efficient N-supplying cover crops do not release appreciable nitrogen to a subsequent crop beyond 6 to 8 weeks from incorporation. This burst of early nitrogen may not synchronize with nitrogen requirements for many vegetable crops, thus at times urban farmers may have to add additional sources of N (Magdoff and Es, 2000).

Many urban soils have been impacted by contamination from previous land uses. Surveys in US cities have found soil lead concentrations above 400 mg kg^{-1} in many urban gardens. On-farm generated organic amendments like animal manure; compost and green manures have some value for low-level remediation due to dilution and stabilization of potential contaminants. Increasing SOM is a critical amelioration method in UA as it helps to retain soil nutrients, immobilize contaminants, and stabilize pH. Increasing SOM also helps to enhance the abundance of microbial communities which are critical for degrading potential contaminants (De Kimpe and Morel, 2000).

Water conservation and use efficiency

In the event of water shortages or decreasing quality of the available water sources, urban producers can access sources such as wastewater, grey water, or harvested rainwater, and apply such water via irrigation usually in a more efficient manner than can rural producers. In areas of water scarcity, productivity should be measured per unit of water (weight or volume), with the goal of irrigation systems reaching efficiency values > 60% (Barthel and Isendhal, 2013).

In rain-fed regions improvement of rainwater capture, selection of drought tolerant varieties, alternative tillage systems, and mulching are critical to secure good harvests. Addition of organic amendments to the soil is vital and many studies are showing that SOM enhances water retention (Altieri *et al.*, 2015). Depending on the soil type, it is estimated that for every 1% increase in SOM, the soil increases its storage capacity in 1.5 l m^{-2}. In other words a 1 % increase in soil organic matter content can hold an additional 178,000 l ha^{-1} of water (Hudson, 1994). Organically rich soils usually contain vesicular-arbuscular mycorrhizal (VAM) fungi, which are of particular significance under water stress conditions, as VAM colonization increases water use efficiency (Auge, 2001). The effect of arbuscular mycorrhizal (AM) colonization by *Glomus clarum* on fruit yield and water use efficiency (WUE) was evaluated in watermelon under various watering regimes. Mycorrhizal plants had significantly higher biomass and fruit yield compared to non-mycorrhizal plants, whether plants were water stressed or not (Kaya *et al.*, 2003).

During dry spells (up to a period of 10 rainless days) a key strategy is to use straw or grass mulch as it can significantly reduce evaporation from the soil surface. Mulching can retard the loss of moisture from the soil and as a result, higher and uniform soil moisture regime can be maintained reducing the irrigation frequency (Ranjan *et al.*, 2017). In vegetable crops, researchers found higher moisture content in the 0–60 cm soil layer of the mulched plots compared to that of the unmulched plots. This moisture difference ranged from 10% one or two days after rainfall to more than 22% over a 2 week period of break in rainfall, indicating that evaporation was high in unmulched plots (Daisley *et al.,* 1988). The greater soil profile moisture under mulch has important implications on the utilization of water by crops and on soil reactions that control the availability of nutrients and biological nitrogen fixation (Hanada, 1991). Clearly, mulching provides many benefits to crop production through soil and water conservation, enhanced soil biological activity and improved chemical and physical properties of the soil (Ranjan *et al.*, 2017).

Crop diversification

Crop diversification in time and space is a key agroecological principle that can be applied to urban farms. By combining plants in intercropping arrangements, crops and trees in agroforestry systems, animals and trees in silvopastoral systems, using legumes as cover crops or in rotations, etc., a farming system becomes more complex as a larger number of different kinds of plants are included, leading to more interactions among arthropods and microorganisms, components of above and below ground food webs (Altieri and Nicholls, 2004). As diversity increases, so do opportunities for coexistence and beneficial interference between species that can enhance agroecosystem sustainability (Nicholls *et al*., 2016).

Temporal diversity: crop rotations

Crop rotation is the practice of growing a sequence of different groups of crop species (legumes, root crops, fruit crops, and leaf crops) in the same area for many seasons. By dividing the garden in 4 plots (each planted to each guild of crops), every successive year each guild moves to the next plot clockwise. Rotating plant families reduces soil-borne diseases and soil-dwelling insects that are specific to certain crop families. Basic rules of a good rotation include alternating between legumes and non-legumes, never planting crops of the same family consecutively, and alternating crops with deep and shallow roots (Karlen *et al*., 1994). As mentioned above, using legumes in the rotation increase available nitrogen in the soil, even after they are harvested, for future crops, thus reducing the need for external nitrogen inputs (Fageria *et al.,* 2005).

Many researchers and practitioners know that rotating plant families reduces soil-borne diseases and soil-dwelling insects that are specific to certain crop families. For example, Maloy and Burkholder (1959) reported that growing beans after wheat resulted in reduced root rot severity and increased yield. They also concluded that a minimum of 3-year rotation with wheat was needed in fields with a history of severe root rot incidence. A number of cover crops and green manures used in rotation schemes can also be effective in suppressing nematode populations and infections (Clark, 2012). Sudan grass (*Sorghum sudanenese* (Steud.) Millsp. & Chase) has been reported as an effective green manure to reduce reproduction of the nematode *Meloidogyne hapla* and, therefore, its damage to lettuce plants (Abawi and Widmer, 2000).

Intercropping

Intercropping involves mixtures of annual crops in the same plot of land at the same time, resulting in increased crop diversity, which improves SOM, soil cover, water retention capacity and microclimatic conditions favoring production (Francis, 1986). Crop diversity also enhances resilience to climatic variability and favors arthropods and microorganisms involved in improved nutrient cycling, soil fertility, and pest regulation (Altieri and Nicholls, 2004).

Synergistic crop combinations include tall and short crops, plants that use resources at different times; shallow- and deep-rooted plants that exploit different soil horizons. Examples include legumes with cereals, tomatoes and basil or beans; lettuce or mescluns between rows of leek or garlic, and arugula under kale (*Brassica oleracea var. sabellica*) Good crop mixtures lead to increased productivity partly due to the process of facilitation, when one crop modifies the environment in a way that benefits a second crop, for example, by lowering the population of a pest, or by releasing nutrients that can be taken up by the second crop.

Over yielding

A combination of two contrasting species leads to greater overall productivity because the mixture can use resources (nutrients, water, and sunlight) more efficiently than separate monocultures. The over yielding of intercrops is measured using the Land Equivalent Ratio (Francis, 1986). When the value is higher than 1, polycultures over yield (i.e. a LER of 1.5 it means that a monoculture requires 50% more land to obtain the same yield of the polyculture). In our experiments at Berkeley, we have obtained LER values >1.5 in combinations of lettuce, mizuna, kale, arugula and others (Table 5).

Table 5. Yields and LER (Land Equivalent Ratio) values of various vegetable crop combinations in an urban farm in Berkeley, California (Altieri, unpublished data).

Cuadro 5. Rendimientos y UET (índices de uso de la tierra) para varias combinaciones de hortalizas en una granja urbana en Berkeley, California (Altieri, datos no publicados).

Crop Species	Monoculture	Polyculture
Mizuna	0.599	0.603
Arugula	0.410	0.334
LER		1.84
Kale	1.11	0.522
Arugula	0.41	0.243
LER		1.06
Green Lettuce	0.501	0.31
Kale	1.11	1.46
LER		1.92
Mizuna	0.599	0.96
Green Lettuce	0.501	0.85
LER		3.2
Mizuna	0.599	0.85
Arugula	0.401	0.27
LER		2.0

Results from a study involving different combinations of peanut, watermelon, okra, cowpea, and pepper planted alone or in various intercropping combinations revealed positive LER values. Within-row combinations with peanut, watermelon and okra and peanut, watermelon, okra and cowpea consistently over yielded in two consecutive years with LER values ranging from 1.17 to 1.25. Intercropping increased yields in almost all instances over their monoculture counterparts (Lithourgidis *et al*., 2011). Furthermore, the intercropping systems more efficiently removed nitrogen from the soils and partially returning it via decomposing biomass, indicating increased resource use efficiency in the intercropped systems (Ouma and Geruto, 2010). Zhang and Li (2003) proposed a competition-recovery production principle based on several years of studies on intercropping of short-season/long-season species. They suggest that interspecific interaction increases growth, nutrient uptake and yield of dominant species, but decreases growth and nutrient uptake of the subordinate species during the co-existence stage. After the dominant species is harvested, the subordinate species has a recovery or complementary process, so that the final yields remain unchanged or even increase compared with corresponding sole species.

Insect pest regulation in diversified urban farms

The literature suggests that diversification in urban farms can achieve positive pest management outcomes, including natural enemy enhancement, reduction of pest abundance, and reduction of crop damage (Altieri and Nicholls, 2004). Many studies conducted on brassica crops (collards, broccoli, brussel sprouts, etc.) have reported four major trends: (a) aphids and flea beetles are more likely to locate and remain on host plants occurring in monocultures than in brassica crops associated with other plant species; (b) pests immigrate into polyculture systems at significantly lower rates than into monoculture systems; pests emigrate from polycultures at significantly higher rates than from monocultures, (c) if main crops are intercropped with trap crops, these plants can divert pests from main crops, thus insect feeding is concentrated on the trap crop, instead of on the crop, and (d) natural enemies are favored in diverse gardens thus, exerting mortality on herbivorous populations (Altieri and Nicholls, 2004).

Studies conducted in California revealed that flea beetle numbers were significantly lower in collards associated with wild mustard, *Brassica campestris*, than in monocultures (Altieri and Gliessman, 1983). Flea beetles preferred this plant over collards, thus flea beetles were diverted from collards resulting in diluted feeding on the collards (Table 6). The authors argued that wild mustards have higher concentrations of allylisothiocyanate (a powerful attractant to flea beetle adults) than collards, and therefore the preference of flea beetles for wild mustard simply reflected different degrees of attraction to the foliage levels of this particular glucosinolate in the weeds and collards. Figure 2, illustrates this preference in the field by showing that population densities of flea beetles on collard plants grown as monocultures are greater than on collards intercropped with wild mustards and with a non host plant such as barley (*Hordeum* vulgare L.) (Altieri and Schmidt, 1986). Although barley as a non-host might have effect a disrupting effect on flea beetle colonization, the trap cropping effect of wild mustards exerted a stronger influence on beetle abundance in this case.

In an urban setting in Albany, California, during summer and fall of 2004, insect populations and yield

Table 6. Flea beetles (*Phyllotreta cruciferae* Goeze, 1771) in various collard cropping systems in Santa Cruz, California (Altieri and Gliessman, 1983).

Cuadro 6. Poblaciones del crisomelido (*Phyllotreta cruciferae* Goeze, 1771) en varios sistemas de produccion de coles en Santa Cruz, California (Altieri and Gliessman, 1983).

	No. of flea beetles		
Cropping system	Per 10 collards*	Per 5 weeds[a]	Damaged Leaves per collard[b]
Collard monoculture			%
Weed-free all season	34.0a	___	54.4a
Weedy all season	6.6b	25.0	29.9b
Collard- bean polyculture			
Weed-free all season	2.3c	___	34.1b
Weedy all season	0.6c	15.0	32.1b

*Means of followed by the same letter in each column are not significantly different (P = 0.05). (all means are averages of three sampling dates).
[a]*Brassica* spp. weeds.
[b]Percent leaves in each collard plant with insect damage

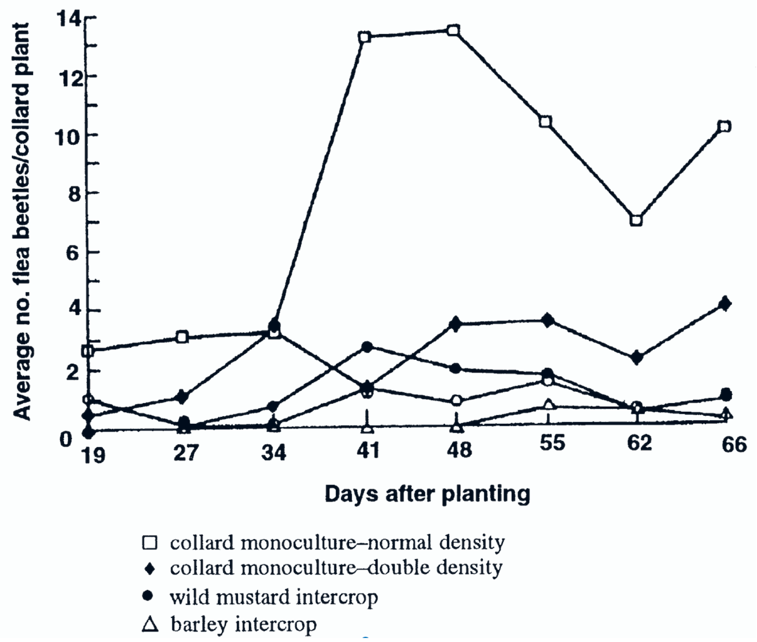

Figure 2. Population trends of *Phyllotreta cruciferae* in collard monocultures and in collard polycultures mixed with a host plant (wild mustard) and a nonhost plant (barley) (Altieri and Schmidt, 1986).

Figura 2. Tendencias poblacionales de *Phyllotreta cruciferae* en mono y policultivos de coles mezcladas con una planta hospedera (mostaza silvestre) y una no hospedera (cebada) (Altieri and Schmidt, 1986).

parameters were monitored in broccoli monoculture and polyculture systems with or without competition from *Brassica* spp. (mustard), or *Fagopyrum esculentum* Moench, 1974 (buckwheat), and with addition of organic (compost) or synthetic fertilizer. Intercropping significantly reduced pest pressure only in the summer and mustard was found to be better than buckwheat at controlling aphids, probably due to mustard being able to serve as a trap crop (Figure 3). A positive effect of intercropping on natural enemies was evident in the summer experiment, when the proximity of flowers significantly enhanced aphid parasitization rates on broccoli. Synthetically fertilized broccoli produced more biomass, but also recruited higher pest numbers. It is known that compost releases mineral nitrogen in the soil at a slower rate than synthetic fertilizer and this has been related to lower foliar nitrogen content leading to reduced pest incidence. Despite lower aphid densities, however, broccoli fertilized with compost consistently had higher parasitization rates than synthetically fertilized plants (Table 7). In summary, intercropping and composting decreased pest abundance in broccoli regardless of interspecific competition from intercropped plants. In addition, depending on the intercropped plant and the growing season (summer vs. fall), intercropping enhanced natural enemies of cabbage aphid in broccoli. The seasonal effectiveness of natural enemies of *B. brassicae* was increased by composting despite lower aphid abundance in compost-fertilized broccoli (Ponti *et al.*, 2007).

A survey of 25 community gardens in the California central coast conducted by Egerer *et al*. (2018) in June and August, found that in June, aphid density increased with host plant volume but decreased with greater floral density, while parasitism was only influenced by aphid density. In August, host plant volume similarly positively affected aphid density and host plant density had a strong negative effect on parasitism. Authors suggested that urban gardeners might be able to reduce aphid pest densities by increasing floral resource density and strategically spatially distributing host plants throughout garden beds. A common recommended strategy to enhance biological pest control is to plant borders or strips of flowers such as buckwheat, sweet alyssum, coriander, wild carrot, phacelia and fennel. If these species are planted early in the season in urban farms, the abundance of syrphid flies, lady bugs and many parasitic wasps could increase as the flowers provide them with pollen and nectar (Altieri and Nicholls, 2005). A higher diversity and abundance of natural enemies early in the season is usually useful in preventing pest population build-up (Mata *et al.,* 2017).

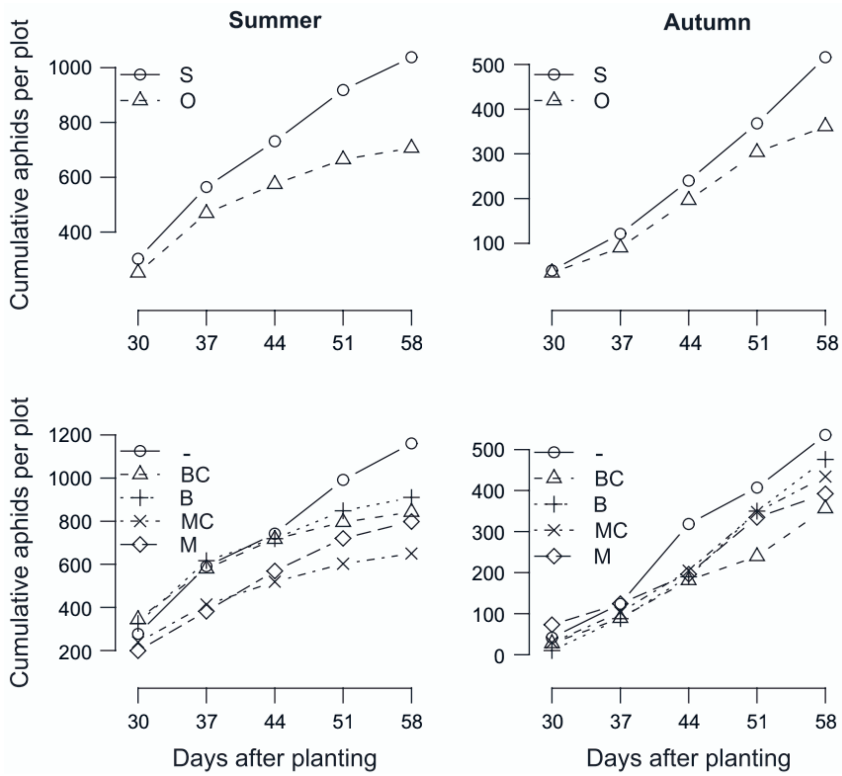

Figure 3. Cumulative counts of aphids on five broccoli plants per plot at the different sampling dates as influenced by cropping system levels ("-" monoculture; B, buckwheat polyculture without competition; BC, buckwheat polyculture with competition; M, mustard polyculture without competition; MC, mustard polyculture with competition) and by fertilizer levels (S, synthetic fertilizer; O, organic fertilizer-compost) in two (summer and fall) experiments at Albany, CA in 2004 (Ponti *et al.*, 2007).

Figura 3. Densidades acumuladas de pulgones en cinco plantas por parcela en diferentes épocas de muestreo según la influencia de sistemas de cultivo ("-" monocultivo; B, policultivos de alforfón sin competencia; BC, policultivo de alforfón con competencia; M, policultivo de mostaza sin competencia; MC, policultivo de mostaza con competencia) y por niveles de fertilización (S, fertilizante sintético; O, fertilizante orgánico-compost) en dos experimentos (verano y otoño) en Albany, California en 2014 (Ponti *et al.*, 2007).

Table 7. Seasonal cabbage aphid parasitism (±SE) by *Diaretiella rapae* (M'Intosh, 1855) during summer and autumn fertilization experiments at Albany, California (Ponti *et al.*, 2007).

Cuadro 7. Parasitismo estacional del pulgon de la col (±DE) por la avispa *Diaretiella rapae* (M'Intosh, 1855) durante experimentos de fertilización en verano y otoño en Albany, California (Ponti *et al.*, 2007).

	% Parasitism	
	Summer[a]	Autumn[b]
Synthetic	4.2 ± 0.4	0.5 ± 0.1
Organic	8.3 ± 1.3	2.5 ± 1.4

[a]P = 0.004 synthetic vs. organic fertilizer ($F_{1,20}$ = 9.97)
[b]P = 0.03 synthetic vs. organic fertilizer ($F_{1,20}$ = 5.14)

CONCLUSIONS

Examples from urban farms around the world suggest that self-sufficiency in terms of vegetables could potentially be achieved at the level of a community or city if such UA farms were re-designed and managed using agroecological principles. Well-designed urban farms can be up to 15 times more productive in terms of total output than rural holdings. In Cuba, an area of just one square meter can provide 20 kg of food a year (200 tomatoes (30 kg) per year, 36 heads of lettuce every 60 days, 10 cabbages every 90 days and 100 onions every 120 days). Considering the average requirements for one person of vegetable crops is about 72 kg year^{-1}, a 10 m^2 bed in an intensive garden can yield up to 200 kg of vegetables per year, potentially providing about 55 % of the yearly vegetable needs of a family of five (Infante, 1986).

A productive UA also requires that citizens have access to sources of green biomass and/or manure as nutrient sources. Some cities provide weekly residential collection for plant debris and food scraps. In 2010, the city of Berkeley, California collected 13,650 tons of residential food and green waste and 6,500 tons of food scraps from commercial customers. This material is processed by a private composting company, which at the end of each month from February to October makes freely available 61-92 m^3 of compost to residents.

Agroecological designs feature well-planned crop diversity, complemented by organic soil management. Together these comprise an effective agroecological strategy to improve nutrient cycling and soil fertility. They also limit nutrient and water losses, reduce impacts of pests, diseases and weeds and enhance overall productivity and resilience of the cropping system (Nicholls *et al*., 2016). But diversifying urban farms *per se* does not necessarily mean that they are being managed agroecologically, unless the collection of crops chosen interacts biologically. Many urban farms are diversified in response to food security or market demands. Such farms do not reach full potential, as the crops do not interact with each other synergistically, often necessitating external conventional or organic inputs of fertilizers or pesticides. The key is for researchers and practitioners to find the right combinations of crops that complement each other to achieve over yielding. Enhancing productivity of urban farms can contribute substantially to improving local food security. In addition, biodiverse UA offers potential to ameliorate a host of urban environmental problems by increasing vegetation cover, which provides a host of ecological services such as conservation of plant and insect biodiversity, uptake of CO_2 and resiliency to weather variability (Faeth *et al.,* 2011).

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