urban science

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Review

Promoting Urban Farming for Creating Sustainable Cities in Nepal

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Abstract: This paper responds to the research question, "can urban farming in Nepal help create sustainable cities?" Especially after the COVID-19 pandemic, urban residents have begun to realize that food transported from long distances is not always reliable. Urban farming can help produce fresh food locally and help urban residents become self-reliant by engaging in healthy eating habits and practicing sustainable agricultural techniques in food-desert areas, while creating a positive impact on the environment through regenerative agricultural methods. In doing so, urban farms can help the growers save on food expenditures and even earn some additional income, while also improving air quality and minimizing the effects of urban heat islands. This practice also helps reduce greenhouse gases through plant carbon use efficiency (CUE), as vegetation carbon dynamics (VCD) can be adjusted while supporting the circular economy. As urban lands command higher prices than agricultural land, urban farming usually happens on residential yards, roofs, balconies, community gardens, and dedicated areas in public parks. Rainwater harvesting and redirecting can help irrigate urban farms, which can be part of rain gardens. The national census of 2021 identified that 66% of Nepal's population lives in urban areas. However, the World Bank (2018) showed that only 21 of Nepal's population was projected to live in urban areas in 2021. It is not debatable that the urbanization process in Nepal is on the rise. Thus, urban agriculture can play an important role in supplementing residents' food needs. Many cities in Nepal have already successfully adapted to urban farming wherein residents grow food on their building sites, balconies, and rooftop, often growing plants in pots, vases, and other types of containers. The UN-Habitat, with the support of the European Union and local agencies, published a rooftop farming training manual (2014), showing the feasibility of urban farming in Nepal. This paper discusses how public-private partnership (PPP) can promote urban agriculture and make the process more effective and attractive to urban-farming households. It also analyzes how a PPP approach also facilitates the use of better technology, advisory support, and use of research extension activities. This paper draws on a literature review, uses remote-sensing imagery data and data from National Census Nepal 2021, and the authors' professional experiences related to best practices in the areas to analyze the benefits and challenges related to urban farming both in Nepal and Arizona, USA. The paper provides recommendations for Nepali cities to maximize the benefit provided by urban farming. It is expected to be useful to Nepali policymakers, government agencies, and nonprofit organizations which promote sustainability, and organic farming with a sustainable supply chain.

Keywords: urban farming; hydroponics; aquaponics; public-private partnership (PPP); greenhouse gas emission avoidance

Citation: Bhattarai, K.; Adhikari, A.P. Promoting Urban Farming for Creating Sustainable Cities in Nepal. *Urban Sci.* **2023**, *7*, 54. https://doi.org/10.3390/urbansci7020054

Academic Editor: Atiq Zaman

Received: 17 March 2023
Revised: 17 April 2023
Accepted: 6 May 2023
Published: 10 May 2023

1. Introduction

City residents have practiced urban farming for centuries. In recent years, there has been a resurgence of interest in it because of concerns about urban food access, sustainability, and food security. Due to its potential to support food security and sustainable agriculture, and because of its lesser impact on the environment than conventional agricultural practices, urban farming is becoming more attractive than before. A Michigan State University study has found that traditionally produced food in the USA is transported by an average distance of almost 1500 miles before it arrives on supermarket shelves [1]. This has many implications, including the unnecessary extra cost of food, increased carbon emission, deterioration of freshness of food, and potential for supply disruption due to inclement weather, pandemics, road closures, strikes, and other causes. For an industrial market economy, such a supply chain is necessary at the present time. However, the practice of urban agriculture can help avoid some of these problems, while also generating part-time jobs.

Urban agriculture attempts to advance sustainable agricultural methods, such as composting, the use of organic fertilizers, and water conservation. It involves a multidisciplinary approach, combining knowledge of soil science, plant physiology, sustainable agriculture, and technology. Crop rotation and companion planting are two other methods urban farmers can utilize to lessen the demand for pesticides and herbicides. The crops are managed using advanced technology involving sensor-based monitoring, automated irrigation systems, and data analysis to maximize crop output. Urban crop farming is regarded as an important agricultural activity for the modern and circular economy, as it can also improve the urban residents' income and reduce agricultural waste.

Of the eight billion people on earth in 2023, more than 55% are already living in urban areas [2] (Ritchie and Roser 2018). Agriculture has been a significant source of food, income, and employment, and it can also help to reduce poverty, increase income levels, and promote prosperity for a projected 9.7 billion people by 2050 [3,4]. The urban population is expected to exceed 75% of the total global population by 2050, making urban agriculture even more important. In light of several persistent issues, such as climate change, greenhouse gas emissions, pollution and waste generation, food shortage, and food waste, agricultural growth through traditional farming is constantly in danger [3]. Weed growth, which annually results in major crop loss, is another serious issue that traditional farmers must contend with [4–6]. Agriculture contributed almost 4% to the global Gross Domestic Product (GDP) in 2018, and it makes up more than 25% of the GDP in some developing nations. Despite the extensive traditional farming, about 9% of the world's population remained hungry in 2020 [3,6].

Theoretically, to feed the growing population, a cultivation area equal to that of the South American continent is needed. In addition, a farming area consisting of almost the size of the African continent is needed for all the animals that are essential to support human activities. This will require bringing almost 57% of the total earth's surface under habitation. However, as almost 57% of the earth's land surface is unhabitable, all human activities must be limited to 43% of the total land surface. Within that 43% area, all types of land use, such as forest, built-up areas, infrastructure, agriculture, water bodies, and various recreational activities, must be accommodated. Currently, of the global land surface, urban areas occupy between one and 3% of the total land area. Concentrating the urban population that would reach 75% of the total global population by 2050 within the urban areas means that urban planning must become smarter than it is today, and that includes the practice of urban agriculture [2].

The traditional agricultural sector has become a polluting, water-intense, and ecologically damaging industry. Urban agriculture (or farming) could help to offset some of these problems by shifting at least part of the agricultural production to the urban farms. Urban farmers must comprehend how plants grow. This involves being aware of how light, temperature, and water affect plant growth [7] and knowing how to spot and deal with pests and diseases that could harm plants. Moreover, it is important to know how using nutrient-rich water instead of soil, as with hydroponics, can help plants grow. This method is particularly helpful in urban settings with limited space for farming and generally poor soil conditions. Understanding plant nutrient needs, water chemistry, and environmental controls is necessary for hydroponic farming systems. To limit their production within smaller spaces, urban farmers frequently adopt clever methods such as vertical farming, rooftops, balconies, and communal gardens. To create the optimum plant-growing conditions, farmers need to amend the soil with fertilizers, check for impurities, and keep an eye on the pH (potential for hydrogen) level of the soil. Urban farmers need to control pests without resorting to hazardous chemicals that could endanger either human health or the environment. This could entail utilizing organic pest management techniques, such as companion planting, or the introduction of beneficial insects.

Urban agriculture (UA), sometimes also known as urban farming, is the practice of growing food within urban areas for personal consumption or small-scale commercial purposes. It consists of growing fruits and vegetables and sometimes raising small animals on-site in residential units and sites for household consumption and for supply into the local markets.

Urban agriculture (UA) is an old practice that has existed since the birth of cities. However, more recently, in the dense and often high-rise-filled modern cities, urban agriculture has not found many practitioners. With the environmental concerns related to transporting foods over long distances, often with their freshness compromised, and after the experience of pandemics such as COVID-19, urban dwellers are increasingly realizing that handy access to freshly grown food on-site is an important backup for food supply in the urban areas.

Hodgson, Campbell, and Bailkey (2011) [8] define urban agriculture as entailing the following:

> " . . . the production of food for personal consumption, education, donation, or sale and includes associated physical and organizational infrastructure, policies, and programs within urban, suburban, and rural built environments. From community and school gardens in small rural towns and commercial farms in first-ring suburbs to rooftop gardens and bee-keeping operations in built-out cities, urban agriculture exists in multiple forms and for multiple purposes (p. 2)."

Urban agriculture implies the growing and marketing (when applicable) of food in urban areas. Urban agriculture often takes place in community gardens, building balconies and rooftops, residential yards, and sometimes in vertical structures. This is seen as supporting food security and promoting individual productivity, community building, and environmental and economic sustainability. Urban farming may take the form of traditional agriculture, hydroponics, aquaponics, vertical farming, and animal raising in space-efficient systems.

Urban agriculture production is typically located on rooftops; balconies; windowsills; indoors; or in the front, back, and side yards of residential units. The production techniques may include normal planting, vase planting, hydroponics, aeroponics, and vertical farms that produce fruits, vegetables, eggs, and meat from small animals. It includes private edible gardens and community and institutional gardens, as well as edible landscapes in public areas such as on parks, road medians, sidewalks, and plazas. Urban-farming produce is mostly for private consumption but can also be for commercial purposes. Hodgson, Campbell, and Bailkey (2011: 20) found that "Urban agriculture helps meet local food needs while promoting environmental sustainability, health, nutrition, and social interaction; creating opportunities for locally controlled food enterprises and economic development; and enhancing community engagement and empowerment".

Urban agriculture provides city and community various benefits related to supplemental income or saving on food costs for families, helping to improve health from the consumption of fresh foods, preserving urban environments, improving community cohesion, reducing the transportation of food, and enhancing the overall sustainability of urban developments. Urban agriculture practices can offset carbon emissions and save households food-related expenses (see authors' example estimates for Nepal in this paper).

There are also some risks and challenges associated with urban agriculture practices. Examples: Smell from compost, flies and worms from soil and plants, and space use conflicts with other uses. Neighbors' concerns with urban animal raising can be another area of conflict. However, on average, urban agriculture can positively contribute towards a healthy and resilient community when combined with good planning strategies.

Urban agriculture attempts to advance sustainable agricultural methods, such as composting, the use of organic fertilizers, and water conservation. It involves a multidisciplinary approach, combining knowledge of soil science, plant physiology, sustainable agriculture, and technology. Crop rotation and companion planting are two other methods urban farmers can utilize to lessen the demand for pesticides and herbicides. The crops are managed using advanced technology involving sensor-based monitoring, automated irrigation systems, and data analysis to maximize crop output. Urban crop farming is regarded as an important agricultural activity for the modern and circular economy, as it can also improve the urban residents' income.

Urban agriculture can also alleviate the pressure caused by the unending need to expand farmlands to feed the growing population. It will also help in reducing the prevalence of diseases that are often associated with the food that is industrially processed and transported over long distances. Furthermore, a public-private partnership in supporting the production and commercialization of urban agriculture production will help make the urban farming process more efficient and productive. Urban farming helps in efficiently bringing back atmospheric carbon into soils through phytotechnologies, which are "plant–based technologies to clean water, soil, air and provide ecosystem services including energy from biomass" [7] (p2). If urban farming can alleviate some of these problems, it will help urban planners if detail investigations are performed to find/explore whether Nepali urban dwellers are practicing urban farming and how such farming is possible. After the state restructuration in Nepal with the promulgation of constitution in 2015, the government classified 66% of Nepali population as urban. If such a large section of Nepali population practices urban farming, obviously, it may help sustain the food supply chain to some extent.

The major objectives of urban farming are (a) to strengthen supply chain to ameliorate food insecurity for fresh and locally produced food to urban neighborhoods; (b) to disseminate the scientific knowledge of agronomy, horticulture, and ecology among local communities; (c) and to mitigate the effects of urban heat islands and carbon emission by lowering food-travel miles, minimizing soil contamination, and best managing of scarce resources such as water and sunlight.

To achieve the above objectives, we organize the remainder of this article as follows. First, it explains what urban farming is. Second, it discusses the theory of urban farming. Third, it provides the background of the study and presents a comparative study between some towns of Arizona and Nepali urban areas. We limit the discussion of urban agriculture in Nepal to between the years of 2017 and 2021 because the actionable state restructuring occurred started from 2017 in Nepal. We excluded the year 2022 from the discussion due to the lack of data. Fourth, it presents food and its impact on human health. Fifth, the paper discusses the issue of mounting food waste and provides justification for how urban farming can help alleviate this problem. Sixth, it analyzes how public and private partnerships (PPPs) can help to strengthen urban farming. Seventh, we present an empirical analysis of how to measure crop production and to examine the relationship between urban expansion and agricultural practices by using simple linear regression models for years 2017 until 2021. Eighth, we present a comparative study between the crop production using traditional farming and urban farming, along with estimates of cost and production and avoidance of carbon emission in the case of Nepal. Finally, the paper presents conclusions and recommendations.

2. Theory of Urban Farming

The first settlements on the earth started in areas with fertile plains. Such settlements later emerged as urban centers, where people from peri-urban areas and remote villages used to have farmers' markets organized on a regular basis. However, those traditions were not enough to meet the requirements of a large urban population. After the harvest, many agricultural products quickly perished, and they needed to be transported to the consumption sites quickly. Since there were no good transportation networks, many of the products decayed during their long transit. To solve this problem, a German economist and agriculture planner, J. H. Von Thunen (1783–1850), in 1826, using the example of Chicago, argued that city farming should be located centrally within an "Isolated State" (Figure 1).

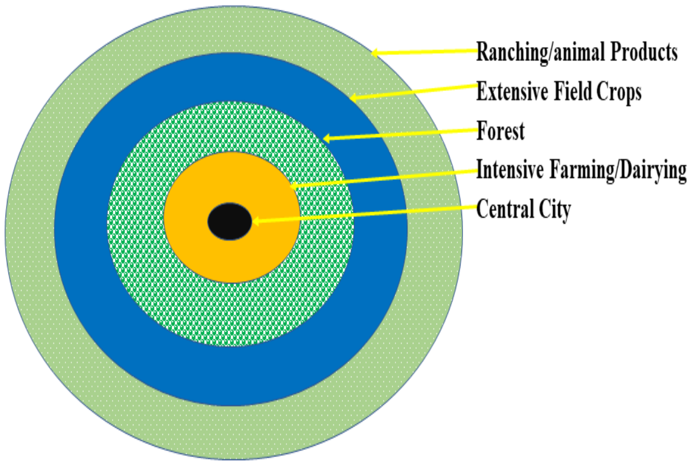

Figure 1. Von Thunen model of land use. (Adapted and modified from [9]).

The Von Thunen model developed a theory of marginal productivity by assuming a uniform land surface without any undulation. Land may be rented to grow crops and transported to different households on an oxcart. The cost of any agricultural products would involve the land rent and transportation cost, as given by Equation (1):

$$L = Y\,(p - c) - Yfm \tag{1}$$

where L = location rent or land value, Y = yield per unit of land, c = cost of production per unit of commodity, p = market price per unit of the produce, f = transport cost of the farm produce to the market (cost per agricultural unit, per unit distance), and m = distance of the farm from the market.

Since the typical isolated state was surrounded by "unoccupied wilderness", especially in a place of food desert, farmers needed to grow agricultural crops and dairy products in the nearby urban areas because agricultural products would perish while being ferried from the production site to the distant urban centers. This was before refrigerated trucks were developed. Farmers largely grew their own food, such as dairy products, fruits, vegetables, eggs, and meat, and consumed it fresh. However, the situation has changed in the last several decades with the development of trucks with refrigerated containers. The long-distance hauling facilities offered by such trucks have made it possible to transport perishable food products over long distances, with less damage to the food. However, the long-distance food transportation process can cause several environmental problems.

First, transporting food increases emissions of various toxic and greenhouse gases. Additionally, the packing and unpacking of food have increased the use of plastic, tin, metal, and paper. The production of these materials contributes 14 to 17% of global anthropogenic emissions [10]. The production, packaging, storage, and transportation of agricultural farm products contribute additional greenhouse gas emission (GHG), which, at present, accounts for 3 to 6% of the total emissions globally [11].

Second, when food is transported over long distances, a significant portion of that food is still wasted. Globally, one-third of all the food produced is wasted, with almost 1.6 billion tons of food being spoiled on the way to the market or date-expired during storage and simply thrown away [12]. Every year, over 600 million people get sick from eating contaminated food [13]. Additionally, long hauling also increases the cost of food. The supply chain can be disrupted for many reasons, such as labor issues, road conditions, inclement weather, the availability of fuel, political unrest, and pandemics, such as COVID-19.

It is useful to capture atmospheric carbon by using carbon sequestration in urban areas too, i.e., trapping carbon by plants to convert it into plant food, biomass, and fruits. Plants can sequester carbon and increase net primary productivity (NPP) per unit area, eventually increasing the gross primary productivity (GPP) [14] of an urban area. Atmospheric carbon can be stored on plant bodies that contribute to plant growth. For instance, a 0.4 carbon use efficiency (CUE) indicates that 40% of the carbon acquired by plants is taken up for the growth and storage of biomass. The CUE of a plant can be measured through biomass [15,16], and the total growth of a plant over an urban area can be converted into GPP [17]. It provides a better understanding of the energy exchange between vegetation and the atmosphere by estimating the CUE of a plant and vegetation carbon dynamics (VCD). A phytotherapy process helps to trap many anthropogenic drivers originating from different sources in the urban environment. These analyses shed some light on the rate of carbon allocation and help to accurately quantify the ability of vegetation to convert carbon to new biomass in urban ecosystems. Furthermore, the CUE assessment would provide new insights into vegetation carbon allocation at regional and global scales. An accurate quantification of CUE for various vegetation types would enhance the performance of earth-system-related models. Since urban farming is performed on a smaller scale, it helps to precisely quantify the CUE and assess the VCD for an urban area. The VCD is a measure of the rapid increase in the atmospheric concentration of CO_2 and other greenhouse gases. Assessing the VCD can help to measure the productivity of various plants [18].

Of the global terrestrial land surface, 71% is habitable. Of the 71%, 33% is arable, and 1% is under urban land uses [19]. A major portion of the population is living in smaller urban areas. Since 2007, the percentage of the urban population (50.14%) has exceeded the rural population (49.86%) (Figure 2) [20]. As the urban population increases, many people have to concentrate their activities in even smaller areas that are urban.

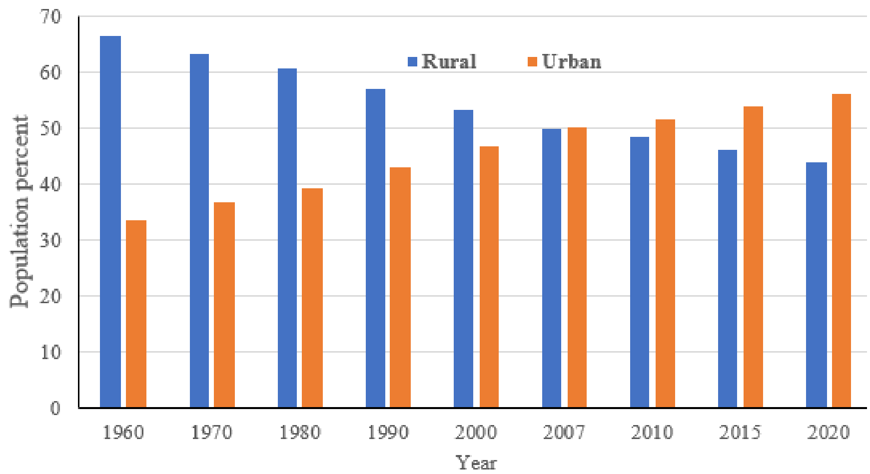

Figure 2. Global rural and urban population percentages (1960–2020) [20].

The rapid growth of urban population has increased food insecurity in cities, and it has overstretched the supply chain, especially at the time of crises such as the COVID-19 pandemic. The United Nations Food and Agriculture Organization (FAO) [21] predicts that, compared to 2022, the global food demand will increase by 70% by 2050. This will put pressure on the already scarce land and water resources. This also means that there is an urgent need for a supplemental approach to address possible urban food shortages.

Urban agriculture has the potential to provide safe and easy access to food for hundreds of millions of people. Urban farming is a way to utilize limited land resources to produce food within urban and peri-urban areas and supply it in response to the daily demand of consumers within a town/city. It applies intensive production methods, using and reusing natural resources and organic urban wastes to yield a diversity of crops and livestock to meet urban food needs. Urban farming offers easy access to fresh and nutritious food. This process was officially recognized by the 15th FAO meeting in January 1999 and subsequently at the World Food Summit in 2002. Since then, its importance has been even more appreciated because, like other service sectors and industries, urban farming provides additional employment and income opportunities for the urbanites. Urban agriculture can create a diverse ecology where fruit trees and vegetables and even fishing could coexist and build an ecologically sustainable circular economy.

Since only small land areas are available for farming in the cities, urban farming is often performed on top of hardscape (pavements, sidewalks, rooftops, and balconies). However, only shallow rooting plants can be planted on raised beds on hardscape. In such a hardscape, if animal manure and chemical fertilizers are used, they generate additional greenhouse gases. However, if organic compost is used, it helps sequester atmospheric carbon within the compost and plant bodies, while using 70 less water. In a smaller area, vertical farming is possible by using compost, wherein every layer can sequester carbon.

Other forms of urban farming on hardscapes include hydroponics, rooftop and balcony, backyard and front yard farming, community gardens, farming in the park, and parking-lot farming. Except for hydroponics, compost made from the by-products of various vegetables and other food products can be used in all types of farming that can not only efficiently sequester carbon but also become a healthy practice because all the products are produced locally and bottom-up, as opposed to a top-down approach (Figure 3). If the urban area has open green spaces, animal manure can be used on the ground. Planting on the open ground allows deep-rooted trees to sequester carbon at a deeper level. In such an environment, the use of animal manure and chemical fertilizers contributes less GHS because most of the carbon is sent back to deeper soil through the deep root system.

Figure 3. Urban farming: A bottom-up approach, as opposed to a top-down conventional approach, to food production and acquisition. Conceptualized and drawn by the authors, using some generic images from the web.

There are several benefits of urban farming. Some of the major benefits include but are not limited to (a) the better taste of vegetable and fruit products; (b) the fact that these are organic and not the genetically modified (GMO) varieties; (c) the use and reuse of wastes; (d) through carbon use efficiency (CPU) and vegetation carbon dynamics (VCD), the net primary productivity (NPP) and overall gross vegetation product (GPP) improve; (e) communities are united through the close monitoring of the production system; (f) educational exhibition; and (g) crime reduction through the involvement of unemployed youths in some creative activities (Figure 4).

Figure 4. Benefits of urban farming. Graphics showing some benefits of locally produced food in urban areas. Conceptualized and drawn by the authors, using some generic images from the web.

3. Materials and Methods

3.1. Materials

We used (a) demographic data and other socioeconomic data from the Central Bureau of Statistics (CBS), Nepal; and (b) land-use and land-cover data at 10 m × 10 m pixel levels that were taken from the global land-cover Sentinel-2 surface reflectance for UTM Zones 44 and 45 N from the Esri website [22]. Using a deep-learning model, we categorized satellite photos by using more than 5 billion manually annotated Sentinel-2 pixels collected from more than 20,000 locations spread across all the world's major biomes. Only a fraction of Nepal's land-use and -cover information for 2017 until 2021 was retrieved, using a shapefile to extract Nepal's information. We identified seven types of land use within the urban administrative territories of Nepal. These include (1) a forest with dense (over 40%) tree canopy cover, (2) shrubland with 10–15% tree crown coverage spread throughout, (3) agricultural land with various crops, (4) snow/ice, (5) glacier-covered places, (6) urban areas, and (7) water (Figure 2). Our primary objective was to investigate how urban dynamics in Nepal's three ecological areas are changing the way land is used and covered. More importantly, our major goals were to see the status of urban agriculture from 2017 to 2021 because Nepal's rural areas have been massively annexed to population centers, and these areas were promoted to an urban definition despite their rural characteristics. We desired to also include the year 2022, but we could not find the appropriate data that would be useful for this research.

3.2. Methods

First, we gathered and analyzed socioeconomic and demographic information from the Central Bureau of Statistics (CBS), Nepal. Since the latest census was completed in 2021, we used that census data. We reviewed the existing literature from various sources.

3.3. Study Focus: USA and Nepal

We chose the State of Arizona in the USA and Nepal as our study areas for two reasons. First, selecting these two contrasting economies and cultures will help scientific communities and readers to learn the science behind urban farming at a glance regarding how urban farming works in both developed and developing countries. Second, our goal is to help facilitate technology transfer between a developed country (USA) and a developing country (Nepal) while also informing the readers about how urban farming can help in sustaining the supply chain, especially when societies face pandemics, environmental crises, and rapid urbanization.

3.4. Urban Agriculture in the USA

The Metro Phoenix region in Arizona, USA, is an urbanized region of almost 5 million people (2022). In most of the municipalities of the metro area, urban agriculture is promoted by the municipal governments for several reasons, including food security, reduction in transportation needs, mitigation of the heat island effect, and self-reliance of households on food. For example, the City of Phoenix (2022) 2025 Food Action Plan states the following: "Achievement of local food system goals results in reduced rates of hunger, obesity, and diet-related diseases through the elimination of food deserts, increasing urban agriculture and adopting zoning, land use guidelines, and other policies to improve the food system". Similarly, the City of Tempe (2014) in Arizona, in its General Plan 2040, includes a strategy to "Expand opportunity for urban agriculture—home gardens, community gardens, urban farms, farmers markets, as well as food availability and accessibility promotes urban agriculture" [23]. Many other cities in Metro Phoenix and elsewhere in Arizona have plans and programs to promote and encourage urban agriculture. Figures 5 and 6 show examples of urban agriculture in Metro Phoenix.

Figure 5. Citrus trees planted in the retention areas in housing areas in Gilbert, Arizona, USA. Photo by Ambika P. Adhikari.

Figure 6. Urban farming in "Agrotopia", a mixed-use urban development in Gilbert, Arizona, USA. Photo by Ambika P. Adhikari.

Agrotopia, a mixed-use community in the burgeoning Town of Gilbert, is an example of how urban agriculture could be woven into the urban fabric and make it more appealing. Agrotopia provides the tour of its urban agriculture to promote the practice and utilizes urban agriculture not only for local food production but also to make the community more attractive for the urban residents. The juxtaposition of urban agriculture and restaurants which use the food produced there is an example of the symbiotic relationship between the urban environment and urban agriculture.

On an experimental basis, the University of Central Missouri (UCM) is growing tomatoes on a hydroponic system inside the greenhouse year-round, without the need for supplemental heating and cooling systems (Figure 7a,b). In a hydroponics system, nutrient water is circulated through the water container and plant. No soil is used, but the plants are supported by various substrates. The substrates provide some holes for air circulation. Under normal temperatures, tomato seeds start germination between 5 and 14 days. Before transplanting plants into the hydroponic system, it is necessary to put blocks into hydroponic baskets, as tomatoes grow quickly.

(**a**)

(**b**)

Figure 7. *Cont.*

(**c**) (**d**)

Figure 7. Tomato growing in hydroponics at the greenhouse of the University of Central Missouri. Photos by Keshav Bhattarai. (**a**–**d**) This is soilless culture. Plants get essential nutrients from circulating /recycling water. Aggregate substrates are used to support plants. This application is useful for households lacking enough spaces to grow plants.

The nutrient-rich water contains all the necessary macro- and micronutrients required by the plants for optimum growth. The water flows from the nutrient tank through the plant system and back into the nutrient tank. The nutrient water is pumped into a trough. The water then slowly returns to the nutrient tank through a valve in the trough. Nutrient-rich water is pumped through a series of thin plastic spaghetti pipes into the buckets. The water supply should be uninterrupted.

Tomatoes perform better when the ambient temperature is between 21 °C and 26 °C and the electrical conductivity is between 2 and 4 milli siemens. (One milli siemens is the electrical conductance equal to 1/1000 of a siemens, which is equal to one ampere per volt.) The optimum water pH ranges from 6 to 6.5 for tomato plants. Calcium is required at the time of fruiting, and lower amounts of potassium nitrate and calcium nitrate are great hydroponic fertilizers. If the pH ranges are not ideal, this condition prevents nitrogen and calcium uptake by the root system even if they are present in the nutrient solution.

3.5. Urban Agricultural in Nepal: Study Area

Most urban dwellers in Nepal are first-generation urbanites. Agriculture is deep-rooted in their blood. Even the highly urbanized places, such as the town in the Kathmandu Valley, Pokhara, Birgunj, Biratnagar, Itahari, Dharan, and Butwal (Figure 8), emerged from recent agricultural places or have agricultural activities in the adjoining areas. Because of this historical nexus between urban development and farming, urban agriculture comes naturally to many of the residents in such cities. More and more urban residents in Nepal are creating rooftop and balcony farms for agriculture and gardening. In more dense urban centers, such as the cities in the Kathmandu Valley and Pokhara, thousands of residents have resorted to urban agriculture on rooftops, on balconies, and in backyards.

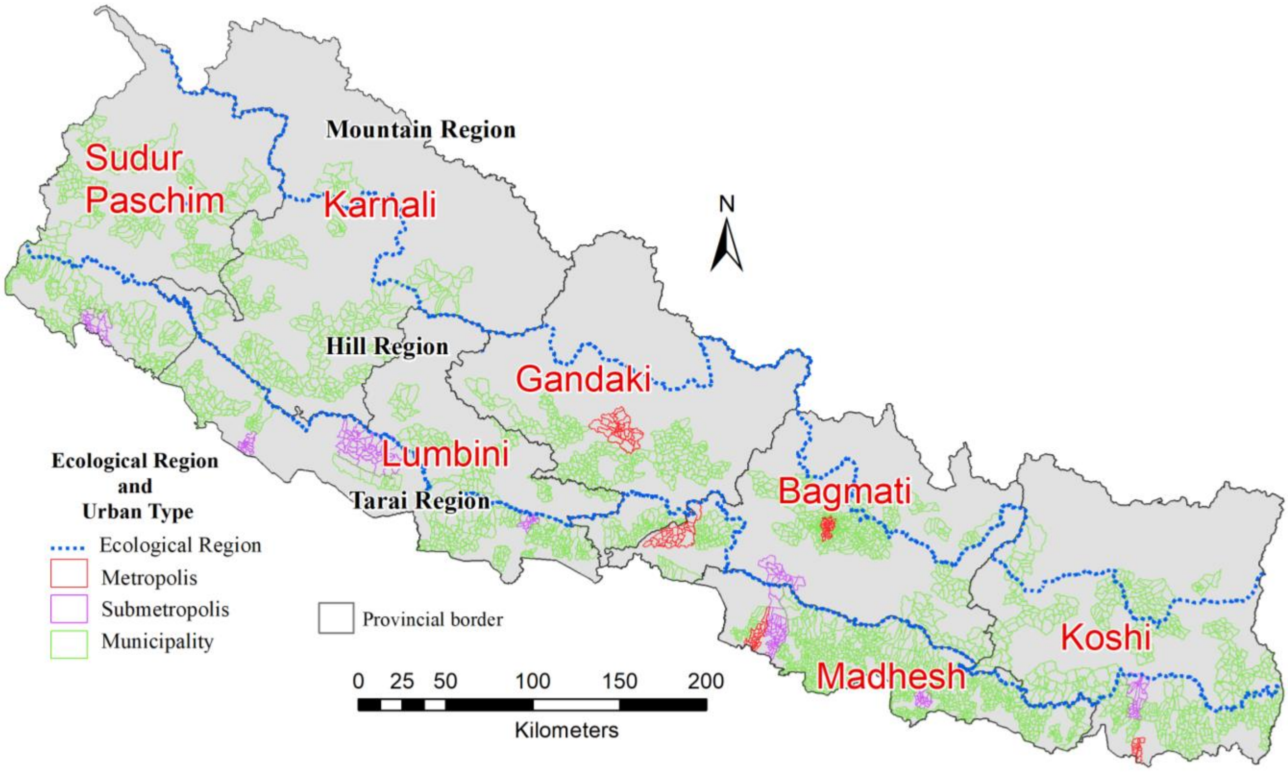

Figure 8. Urban population distribution in Nepal. Map by the authors. Source: [24] CBS (2021).

Table 1 presents a summary of built-up in urban areas and agricultural land within all the urban areas in hectares in seven provinces and three ecological zones of Nepal. These data suggest that each urban area has some agricultural land, and, in each province, agricultural activities did not decrease when urban areas increased. Though many agricultural lands have been plotted to convert into the building sites, Table 1 indicates that farming activities are continuing in different places, such as balconies, backyards, and open spaces.

Table 1. Land-use statistics computed from 10 m × 10 m centennial remotely sensed data. (Images of UTM 45 and 44 zones were classified using a deep-learning system.)

Province	Land Areas in Hectares in Various Provinces Occupied by Urban Agriculture and Urban Built-In Areas									
	Y2017		Y2018		Y2019		Y2020		Y2021	
	Agri	Urban	Agri	Urban	Agri	Urban	Agri	Urban	Agri	Urban
Koshi	1662.39	480.35	1681.63	512.43	1672.53	546.01	1598.54	613.38	1593.52	577.07
Madhesh	3431.91	508.75	3382.89	567.56	3455.33	558.83	3335.22	618.48	3253.35	671.21
Bagmati	688.95	680.11	680.29	710.26	661.21	777.65	639.10	836.62	605.07	795.92
Gandaki	332.74	199.98	317.37	210.07	319.42	232.93	320.02	260.56	288.87	228.23
Lumbini	2080.54	385.29	2067.81	413.51	2052.55	442.18	1996.69	515.45	1999.27	513.26
Karnali	225.12	54.91	193.78	57.41	201.49	70.77	179.79	97.36	151.29	74.59
Sudur Paschim	1147.67	149.34	1132.58	172.81	1108.77	205.42	1072.49	251.84	1027.11	263.78
Total	8387.28	3640.77	9456.35	2644.05	9471.3	2833.79	9141.85	3193.69	8918.48	3124.06

Although the Nepal government redefined many existing rural councils and municipalities in 2017, several municipalities still retain their rural characters. Thus, it is obvious that they have more agricultural land than the built-up in areas. To look at the trends in urban farming between 2017 and 2021, we also looked at the urban farming in metropolises and sub-metropolises because these large cities have been the major attraction centers from all over Nepal. Even in the large cities, we observed similar trends of urban farming (Table 2).

Table 2. Agricultural land areas within the urban border and urban built-up area (hectares) in metropolitan and sub-metropolitan cities in Nepal.

Year	Land Area (Hectares)	
	Agriculture Area	**Urban Built-Up Area**
2017	1236.97	566.23
2018	1227.43	590.87
2019	1202.38	631.73
2020	1161.66	674.72
2021	1152.56	682.69
Total	5981.00	3146.24

In 2015, the UN Habitat, in cooperation with the Kathmandu Municipality, European Union, and a local non-profit ENPHO, published a 56-page-long training manual to help the urban residents cultivate urban agriculture. This manual, which was authored by Dr. Bharat Kumar Poudyal, is called the *Training Guidebook for Rooftop and Balcony Agriculture* [25]. The guidebook contains knowledge and information about the usefulness and benefits of balcony and rooftop agriculture, human needs for nutrition, the daily needed quantities of fruits and vegetable for an individual, the best location for balcony and rooftop farming, and the most suitable types of plants and vegetables for urban farming (Figure 9a,b). The manual also includes lessons about the suitable types of soils, compost, irrigation, trellises, good and bad insects, and insect control and the various techniques and technologies for urban agriculture.

(**a**) (**b**)

Figure 9. (**a**) Terrace agriculture in Kathmandu, Nepal. Photo by Jyoti Sherchan (with permission). (**b**) Terrace agriculture in Kathmandu, Nepal. Photo by Jyoti Sherchan (with permission).

A training workshop in Nepal conducted in cooperation with the United Nations Framework Climate Change Conventions (UNFCCC), with 250 participating families, found that rooftop farming can cover 50% of domestic vegetable consumption needs and avoid 110 metric tons of carbon dioxide emission reductions per year [26].

In Nepal, urban agriculture can help provide many benefits to the city residents, including food security, food self-reliance, savings in food expenditures, and income supplementation for the families. In addition, urban agriculture can help reduce the emissions of greenhouse gases and provide other environmental benefits, including waste reduction and minimizing road congestion. This practice can also help to provide safeguards to counter the unpredictability of the food supply due to road damages, border blockades, and pandemics.

Except for a few well-established cities, most of Nepal's new urban centers were just reclassified by the government and still retain many rural characteristics. Many residents are still practicing agriculture in small tracts of land, while they have been classified as urban residents. Similarly, as urban areas grow, the adjoining agricultural lands also begin to gradually join urban life. These areas are often called peri-urban areas. Because of these differences in urban traits, the urban agriculture practice and potential will also be different in these areas. In denser and more mature urban areas, urban agriculture will mainly happen on rooftops, on balconies, and in yards in the building lots, whereas in the newly urbanizing and peri-urban areas, in addition to these locations, urban open spaces can also be used for urban farming.

As shown in Figure 8, unlike in the overly crowded Kathmandu Valley and other large towns such as Nepalgunj, Pokhara, Birgunj, Dharan, Itahari, Biratnagar, and other areas, many areas are legally defined as urban after they met the population threshold.

These legally defined urban areas do not have the urban infrastructure, services, and amenities, and they often continue to have rural characteristics. In Figure 9, the black areas represent the true built-in urban area, and the pink area represents the administrative boundary of the urban areas. This suggests that there are many areas that can be called "*ruralopolises*", where urban and rural areas are intermingling, forming an urban–rural continuum. In these areas, community farming or open-area farming activities are possible. Open areas can be used for urban farming with deep-rooted trees on deep soils. Deep-rooted trees help sequester carbon and restore atmospheric carbon in the soil. Thus, the urban-farming technique not only can contribute to atmospheric amelioration but also to human health and food security.

In Nepal, urban areas are developing in different stages, and urban farming is emerging in different forms (Table 3). In the dense and well-developed urban centers, urban agriculture happens in smaller hardscapes on and around the buildings. In suburban areas, urban agriculture can be seen on the front, back, and side yards of residential lots. In emerging urban areas, urban farming can be found on the several vacant lots and open spaces spread across the cities and towns.

Table 3. A schematic depiction of the stages of urbanization and urban agriculture potential in Nepal. Conceptualized and drawn by the authors.

Stage of Urbanization	Typical Characteristics and Examples	Typical Locations and Types for Urban Agriculture
High-density urban core	High-rise, mid-rise, high-density areas Kathmandu and Lalitpur central core	Rooftops, balconies, indoor plants, hydroponics, and plants in vases
Suburban	Single family and low-density multifamily Outer ring road settlements in the Kathmandu Valley	Front, back, and side yards; porches; balconies; and rooftops
Peri-urban	Agricultural areas being converted into urban ones Immediate boundaries of cities and towns	Front, back, and side yards; and community parks and gardens
Newly urbanizing	Newly defined as urban, transitioning from agriculture to urban Itaharti, Tokha, and Lekhanath	Front, back, and side yards; and adjoining and interior vacant lands

4. Food and Human Health

Food is produced and processed that gets transported to markets near the population centers. This practice has often been the cause of several health problems such as diabetes, lung disease, cancer, and cardiac issues, to name a few. Despite recent advances in high-quality drugs, better diagnosis, better hospitals, and advances in biomedical research, people are suffering from many more new diseases. Most of these causes are due to our sedentary lifestyles and the processed food that depends on insecticides and antibiotics.

Food can have a major impact on individual health and well-being and on the physical environment. To meet the food needs of the growing population, producers use chemical fertilizers, growth hormones, and antibiotics to protect animals and plants against diseases. To expand farmland, many forest areas are burnt down, emitting significant amounts of greenhouse gases. The modern agricultural practice has massively over-farmed lands, and the natural fertility of the soil can sometimes be completely wiped out. Farmers need to apply more chemical fertilizers to bring back soil fertility. For high levels of production, many farmlands are planted with commercial monocrops supported by fertilizers and pesticides. Many of these products require a lot of fossil fuels to farm and transport food.

Many of the vegetables and fruits come packed in plastic bags pumped with nitrogen to protect them from bacteria. This is a very inefficient and unsustainable way to produce and supply food because producers must pack and transport food often with refrigeration over long distances. The whole system is completely dependent on fossil fuel, from tilling the land to packing to transporting packed food and disposing of the waste.

On a global scale, half the world's arable land and 30% of the world's water have already been used. Producing food in urban areas for individual consumption and local supply could mitigate some of the problems described earlier. Urban areas are short of space, but growing food can start in aquaponics facilities in smaller areas. Aquaponics is a way to grow fish and utilize their waste as nutrients for plants. Fish produce ammonia as a by-product, which is a waste. If this ammonia is left in water, it builds up and becomes toxic. However, it is possible to pump out ammonia-rich water into a separate biofilter. In this ammonia-rich water, microorganisms can convert waste ammonia into a very useful fertilizer. Then, nitrate-rich fertilizer can be pumped out and fed to plants whose roots may be suspended in water and draw out all that nutrient. Eventually, the water becomes nitrate free for the fish. It becomes an efficient closed-loop ecosystem that is sustainable and scalable, and it is not wasteful. Aquaponics can be fully integrated into the urban farming system. We can use fish and utilize their waste to convert it into fertilizer, and that fertilizer can be transformed into nutrients for plants. Plants and fish can be symbiotically maintained in a healthy environment in a closed-loop ecosystem.

Coffee and tea waste products can be recycled to help crops grow. After preparing coffee and tea, people discard the ground coffee and tea as waste. Using a biodegradable pot, mushrooms can be grown on coffee and tea substrate. Once the mushroom is harvested, the leftovers can be fed to worms because they eat waste products. This closed-loop circuit can convert the inputs into three valuable outputs. First, fish use water to intake diffused oxygen, but then they discharge nitrate into the water, making the water polluted. Second, the polluted water becomes a nutrient for plants. Plants purify the wastewater and make this water reusable for fish, while generating oxygen for humans. Third, fish by-products after using the flesh can be utilized to grow mushrooms. Mushrooms release CO_2 that can be given to plants. Any excess products can be fed into an anaerobic digester which produces all the energy to heat and power an integrated urban farm.

Urban farming is a response to the increase in population, shortages of food and agricultural land [27], and increasingly complex relationships between the surrounding environment with sociocultural activities—the bionomics [28]. It is also an antidote to minimizing the losses of food grains from the time of harvest up to the end uses and to mitigating various environmental problems [29]. The shortage of food in local markets was highlighted with the outbreak of the COVID-19 pandemic when the food supply chain broke down. The pandemic not only created shortages of materials required to produce food, but it also led to a decrease in food production by around 3% [30]. All of these factors seriously disrupted the global supply chains [31]. In these types of situations, urban farming can provide a cushion between commercial agriculture and urban communities. Urban farming can help reduce food importation and reduce food supply chains by growing a wide variety of food all year round, using both soils and soilless media such as aeroponics or hydroponics. Since each agricultural crop is tended personally and manually, the food production per unit area of land also remains high [31]. As the production is at the doorstep, fresh food can be served within a few hours of harvest. For example, in Singapore, urban tillers deliver food within eight hours of harvesting. Likewise, in Indonesia, farmers have developed an e-grocery platform named Sayurbox, where customers can buy groceries directly from the farmers that are delivered quickly [31].

Using the 21st century technology, urban farming could act as an antidote to various obstacles such as the transportation problems emanating from the shortages of fossil fuels [32]. Urban farming can help to minimize 21 and 37% of anthropogenic gases emitted from transportation of agricultural products [33]. Urban farming also helps in minimizing the levels of soil and water pollution resulting from excessive uses of fertilizers in commercial farming. Such an approach could be critical in mitigating the impacts of climate, while financially protecting farmers. Agricultural produce is consumed in the household or locally, rather than being taken away for marketing. This will improve the efficiency of the whole food operation. Urban farming can enhance food security [34] at local, regional, and national levels, while reducing food wastes and making the community prosperous through the enhancement and preservation of cultural traditions. It also involves family members in the food production process and supplying food to the needy populations [35].

Because of the targeted use, urban farming generally uses less water per unit of production than conventional farming, and it follows the notion of the circular economy. In a circular economy, almost all the activities are monetized, wastes are fully recycled and utilized, and food becomes completely organic. For example, all the stems of the salads and the peels of the cucumber, potato, orange, and sweet potato are fed to plants, and the by-products have monetary value. Algae can be used to convert it into fertilizer. Using modern technology, emission from vehicles is tapped and mixed with algae at the drainage point of sewage pipes. As emission is fed to the sewage water, algae consume emitted gases tapped from vehicles and industries. This emission is utilized by algae, and algae grow profusely and can be used to make fertilizer. In the Kathmandu Valley, recently, algae have been converted into synthetic leather by students at the Institute of Engineering at Pulchowk, Lalitpur. Additionally, algae can be used as mulch to retain soil moisture, which helps improve crop production. For example, it has been reported that potato yield with algae mulching was 10 times more than from the traditional farming methods in open areas [36].

In a highly dense city like those in the Kathmandu Valley, shallow-rooted vegetables are grown on rooftops, on balconies, in façades, indoors, in windows [36,37] of abandoned buildings, and in interstitial spaces between legal lands. Taller buildings obstruct the solar radiation, thus hindering the process of photosynthesis [38]. These built-in infrastructures offer very little room to produce vegetables and fruit; often, crops are grown on vertical structures [39]. These spaces do not have the provisions required to grow deep-rooted plants. In vertical structures, often light becomes insufficient. To supplement this solar radiation, LED light is used. In such narrow spaces, using animal dung to grow crops emits methane gas; however, using compost helps in sequestering greenhouse gases.

Light Emitting Diode (LED)-produced light can be used to sustain light intensity in a controlled environment. This will help create more efficient growth and a much higher yield per growing area. Several crops with adventitious roots can be grown in biodegradable pots such as those made from coconut husk. For example, mushrooms, lettuce, kale, cauliflower, broccoli, pepper, and zucchini can be grown in such pots. In addition to these crops, other tubers and legumes can be cultivated on an urban rooftop in a horizontal manner. However, in peri-urban farms, they could be grown in a horizontal manner directly on the ground soil in the open spaces on building sites. It is estimated that gray area farming may contribute to 5 and 10% of the global production, while also ameliorating global climate change [40,41].

If urban and peri-urban areas are efficiently utilized to produce agricultural crops, the food produced there can be enough to feed approximately 30% of the total urban population in different geographic regions of the world [42]. Coffee and tea wastes, along with the barks peeled from cucumbers and potatoes and the stems and leaves from the salad can be used to grow such agricultural crops. Though such crops require water, the quantity of water used is 70% less than in the traditional farms for the same amount of harvest. Urban farming helps in cooling the urban areas by using less water and less space and mitigating the heat radiated by built-up hard surfaces [36]. Ambient cooling happens in two ways. First, soil moisture cools the nearby environment, and second, evapotranspiration and oxygen generated from plants also contribute to the cooling of the environment. Thus, urban farming can contribute to accomplishing twin goals, increase in local food production and environmental cooling. Most importantly, urban farming will help to reduce the mounting food waste.

4.1. The Mounting Food Waste

Even though the world has been facing food shortages, the global food system has become incredibly wasteful. A large amount of energy, water, and land is used to grow food at commercial farms. The produced food is transported to various places to make it available to needy people. The transportation of food over long distances becomes an inefficient operation. Global data suggest that 10% of food is lost during cultivation, 7% is lost during the harvest, 12% is lost during the processing or point-of-sale, and another 1% is lost after it has been purchased or sold. This means that a total of over a third of the food produced globally is wasted in the production and delivery process. Urban food production involves a short supply chain because most of the products will be consumed locally [43]. While doing so, circular economic activities become vibrant and diversified. A circular economy not only contributes to the creation of employment but also contributes to mitigating the negative effects of future food system disruptions. A public-private partnership (PPP) approach may be instrumental in this endeavor.

4.2. Public-Private Partnership (PPP)

Gerrard (2001) defines public-private partnerships (PPPs) as those that "combine the deployment of private sector capital and, sometimes, public sector capital to improve public services or the management of public sector assets". Public and private bodies can work together to pool resources and funds to leverage agricultural technology [44]. In PPPs, public institutions and private individuals collaborate to consolidate isolated approaches, resources, and services to cope with the challenges faced by farming communities [45]. The state offers logistic support, a legal framework, a working avenue, and field resources. Academic and research institutions can assist with physical infrastructure, and private organizations can support technology and innovative research.

PPP helps in unlocking digital advisory services to enhance productivity, along with the improvement of soil health and enriching weather information, using various sensors. Digital advising on agronomic services, financing, insurance services, and weather patterns helps landowners to improve farm production. The private sector becomes critical in the development of innovative solutions that provide expertise in plant sciences, genomics, and bioinformatics. However, the private sector is involved in programs only when there is a chance for commercial incentive. Small farmers will use services from the private sector only if there is a financial return. Thus, PPP eventually helps create a bridge between markets, services, and technologies. Advanced technology may include bio-fortification, a method of breeding techniques to improve seed variety to accomplish objectives of genetically engineering food variety that can provide richer minerals, vitamins, and micronutrients and can be cultivated cost-effectively and sustainably [44].

Under the PPP programs, farmers can obtain services in emerging technologies such as artificial intelligence (AI), the internet of things (IOT), blockchain, and drones at competitive prices. Several research organizations in Nepal, such as the Nepal Agricultural Research Council (NARC), Agricultural and Forestry University, National Commercial Crop Research Centre, National Horticulture Research Center, and agriculture research stations located across the country, having facilities for testing and validating information with high credibility, can provide services to farmers. The existing body of agricultural research from universities and other institutions can be better leveraged to scale down or up any work performed by private agricultural technology. Such a vibrant entrepreneurship culture among all the innovators, including students, faculty, entrepreneurs, and grassroots innovators, and especially youth, women, and farmers, can encourage people to work together and produce innovative ideas to boost agricultural production.

The endeavor of PPP fails if it is not operated transparently. However, open communication does not always come naturally, as individuals would not feel comfortable unless benefits and intellectual property rights are assured and transparency is maintained. Investment happens only when fundamental commercial rights are assured to entrepreneurs. PPPs may not be the right choice to solve every challenge in agriculture because entrepreneurs would act very carefully on a smaller scale. If private investors are assured of the security of their investment, only then they will agree to make investments in agriculture.

The importance of PPP was realized during 2020–2022, when the global food supply chain system was disrupted due to the COVID-19 pandemic, and the government alone was not able to address the shortcomings. Additionally, the war in Ukraine that began in 2022 has massively pressured the agricultural sector in both developed and developing countries to provide more sustainable agricultural options, while also mitigating the environmental issues [46].

5. Empirical Analysis

Agriculturists have been developing various methods to utilize different urban spaces, for example, rooftops, indoor farming, and hydroponics, and compare their productivities with soil-based agriculture. A comparative analysis of the productivities calculated using Equation (2) reveals that urban farming performs better per unit of investment and space for various crop products (Table 4) [36]:

$$AM_y = \overline{X} = \frac{\sum x_i}{n} \quad (2)$$

where x_i corresponds to the yield value (in kg m^{-2}cycle^{-1}) for observation i (i = 1 to n), and n is the sample size.

In urban agricultural systems, crops are grown either in a hydroponic system/aquaponic system (Figure 7) or a soil-based system [47]. Equation (2) is appropriate only if the crop is grown in a soil-based system that will include the use of compost or manure.

Table 4. A comparison between urban farming and traditional farming.

Crops	Production (kg. per sq. Meter per Cycle)	
	Urban Farm	**Traditional Farm**
Tomato	8.7	3.7
Chilly	4.2	1.4
Peeper	5.5	1.8
Lettuce and chicory		
Beans	1.5	1.2

Table 4. *Cont.*

Crops	Production (kg. per sq. Meter per Cycle)	
	Urban Farm	**Traditional Farm**
Cabbages	3.6	2.9
Cauliflowers	0.57	0.55
Broccoli	0.61	0.46
Maize	2.5	2.22
Paddy	0.44	0.35
Roots and tubers	3.8	1.3
Oil crops	0.85	0.34
Vegetables	4.6	1.9
Primary fruits	2.2	1.4
Cereals	0.62	0.40
Sugar	5.3	6.9
Fiber crops	0.42	0.01
Average production in kg per sq. meter	2.84	1.68
Average production in kg per hectare	28,400	16,800

Source: [48].

5.1. Results: Linear Regression Models

We used regression models to examine the relationships between agricultural areas exclusively within the urban boundaries and total urban built-up areas within the same administrative urban boundaries. These data were derived from the analysis of remotely sensed data downloaded from the Esri website. We set the urban land area as the dependent variable and agriculture land area, forest, and shrublands as independent variables for years 2017 until 2021. Regression outputs are given in Appendix A. Our hypothesis is that, despite urban growth, there was no decrease in agricultural activity in years 2017 until 2021.

During the field visits by one of the authors in 2017, 2018, and 2019, we saw that several agricultural lands in Nepal were being plotted for buildings. However, satellite observations for the years of 2017 to 2021 reveal no negative relationship between urban growth and agricultural land within the urban territory (Figures 10 and 11a–e). The statistics revealed from the analysis of satellite imagery taken from 2017 to 2021 show no decrease in overall urban farm areas despite the expansion of urban built-up area. Simply put, there is no decrease in overall urban farm areas (Figure 10) in all the years of observations within the urban delineated boundaries (Figure 8), and a positive correlation ($r = 0.999$) exists between urban and farm areas within the urban territories. Correlations between urban areas and agriculture, forest, and shrubland are in decreasing order. With agriculture, it is higher, but the correlation between urban and forest and shrubland decreased in successive years. These results reveal that, as urban areas increase in successive years, the forest and shrub areas decrease, whereas large agricultural areas shrink, but the agricultural crops' greenery, as depicted by satellite imagery, has increased along with urban areas (Figure 11a–e). The same sensor, however, recorded a decrease in forest and shrublands between 2017 and 2021 (Figure 10). This is also evidenced from the negative coefficients for forest and shrubland for the years 2017 to 2021, and the positive coefficients for agriculture for the corresponding years, with t-values higher than 8 and p-values < 0.00001 for all observation years, suggest that the urban farming area has not decreased despite its low rate of increase; however, forest and shrubland has decreased, showing $p \leq 0.00001$ and t-value being larger than negative 10 and negative β coefficients. Detailed outputs of the regression analyses for years 2017 until 2021 are given in Appendix A.

Figure 10 clearly depicts the changes (reduction) in forest and shrubland, but agricultural land and urban built-up areas are increasingly showing a perfect Pearson correlation (r = 0.9999). During our field visits between 2017 and 2019, we observed that, in several places, forested areas were degraded due to human activities turning such areas into shrublands, and when human interferences were reduced, after some time, the same areas experienced a comeback with forest stands. These are the reasons why there are changes between forest and shrubland. In areas that are in proximity to highways and district headquarters, there has been increasing human interference in the forested ecosystem. Repeated interferences have turned the forested areas into shrublands. These shrublands are often converted into urban areas (Table 5). Likewise, with the increase in land prices for urban expansion, many agricultural lands are plotted for urban built-up areas. These practices have led to the decrease in farmlands within the urban administrative territories. However, people have grown crops in their backyard, on their balcony, and in any available spaces to produce fresh agricultural products. These practices have compensated for the production on agricultural lands that were converted to built-up areas. This is why the β-coefficient values for independent variable agriculture for all the observed years from 2017 to 2021 were positive, with high t-values and *p*-values lower than 0.00001 (Appendix A). Both agricultural land and urban areas have similar trends in their expansion, albeit at different proportions. We argue that, despite a decrease in physical agricultural areas, increasing greenery in open urban spaces, including vertical and horizontal farming, has given false an impression that urban agriculture has not decreased and there are positive correlations between urban land and agricultural lands (Figure 11). These trends indicate that urban farming has become a practice in Nepal (Figure 9a,b), especially after the interrupted supply chain due to COVID-19.

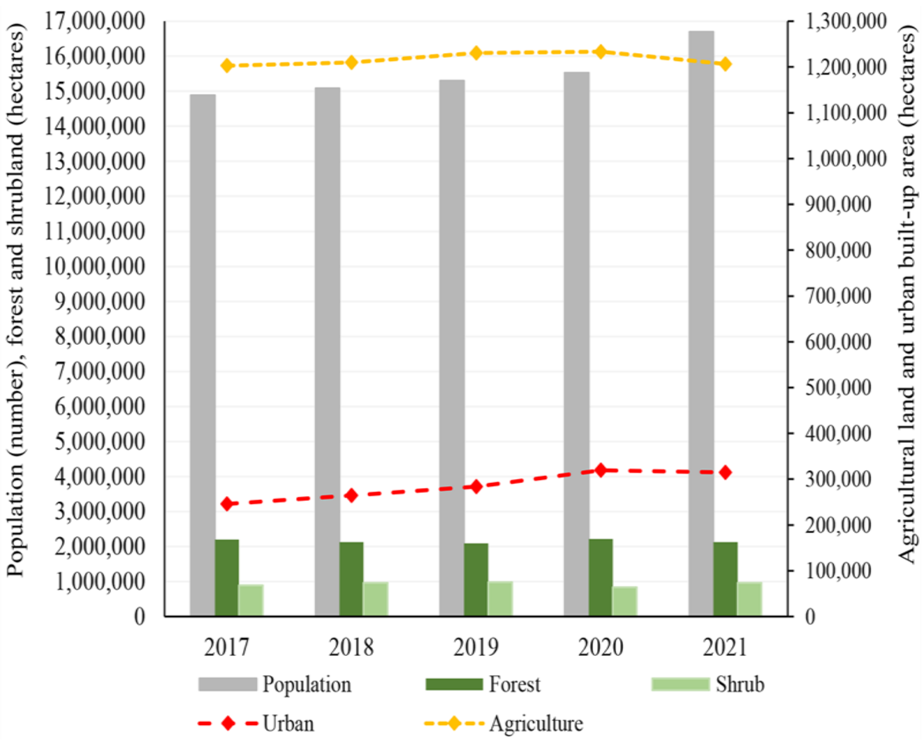

Figure 10. Relationship between urban growth and agricultural areas in Nepali urban territories [22,24].

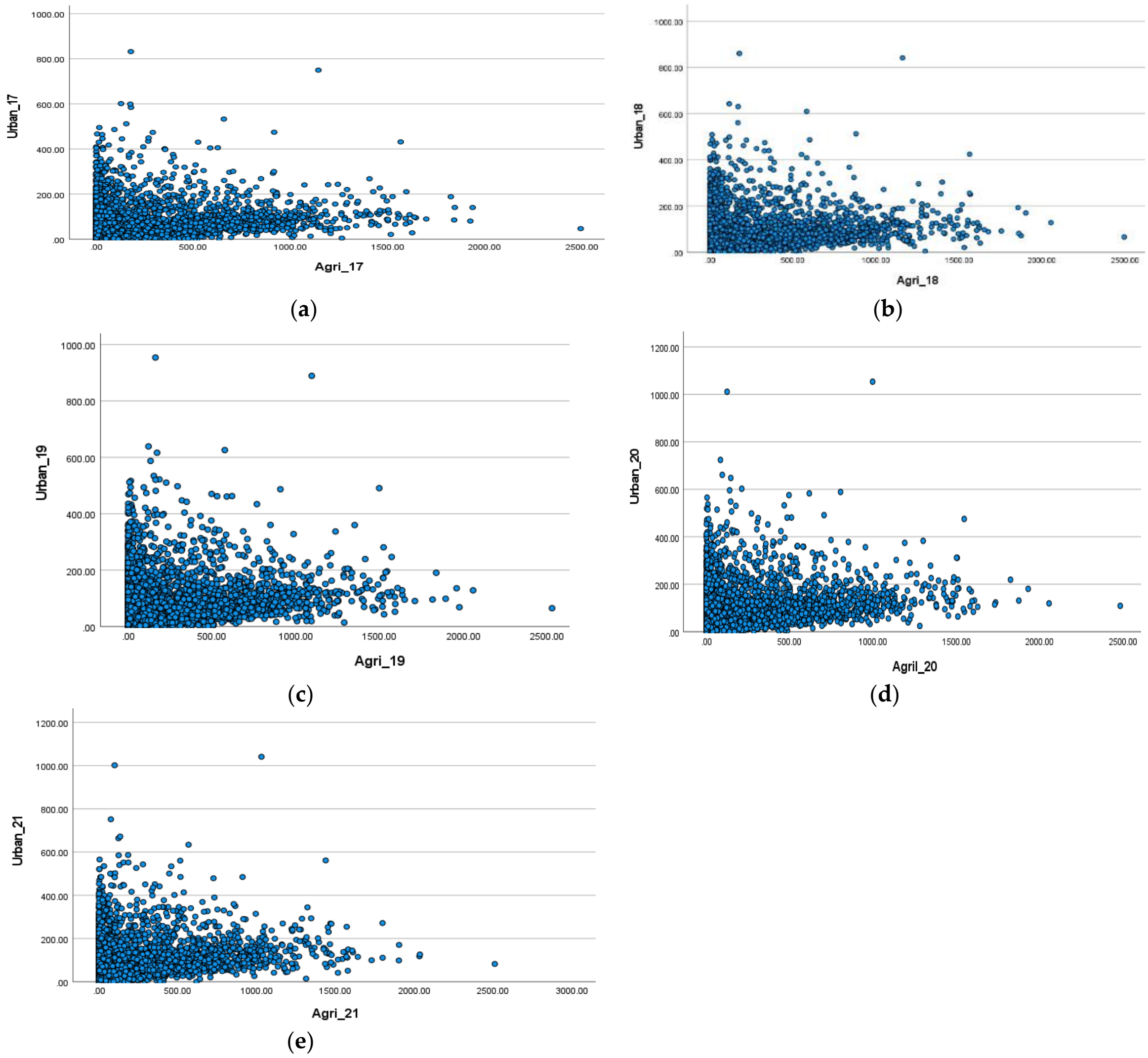

Figure 11. Relationships between urban area (*Y*-axis) and agricultural land (*X*-axis) within the urban boundaries in (**a**) 2017, (**b**) 2018, (**c**) 2019, (**d**) 2020, and (**e**) 2021. Each year, there is a positive relationship between the urban area and urban agricultural land. Though a lot of traditional agricultural land has been converted into built-up areas, the overall greenery areas within the urban boundaries are also increasing in all years because of the farming practices within urban areas.

Table 5. Number of total households, total population, urban, agriculture, forest, and shrubland in Nepal. These activities are confined within the urban territories. Households and population (people) are in number; urban, agriculture, forest, and shrubland are in hectares. These figures come from Census Bureau of Statistics of Nepal (2021) [49], analysis of satellite images for 2017 to 2021 [22,24].

Description	2017	2018	2019	2020	2021
Household	3,179,501	3,223,011	3,269,769	3,317,878	3,568,461
Population	14,885,696	15,081,759	15,300,557	15,525,679	16,698,585
Urban	245,862	264,399	283,380	319,366	314,403
Agriculture	956,929	945,631	947,128	914,173	891,844
Forest	2,198,796	2,124,194	2,086,774	2,211,531	2,122,948
Shrub	887,922	966,543	978,629	840,674	959,362
Water	37,317	33,195	33,376	38,715	38,027

Nepal was rapidly urbanized, but, still, many urban areas have rural characters. We focused our analysis on 2017 to 2021 because, after the state restructuration of Nepal, along with the implementation of constitution of 2015, many Nepali rural areas were classified as urban despite their rural characteristics. Thus, we took the base year as 2017 to conduct this analysis. Unfortunately, we could not find data for 2022, and we excluded the year 2022 from the analysis and limited our analysis to the years 2017 to 2021.

5.2. Estimated Avoidance of Greenhouse Gases by Urban Agriculture in Nepal

Urban agriculture can help avoid emissions of greenhouse gases caused when traditionally produced agricultural products are transported to the urban markets. Obviously, the absorbed carbon dioxide will be changed into biomass and fruit production. Puigdeta et al. (2021) [50] and the World Bank (2019 and 2020) [51] estimated that it is possible to absorb 205 kg of CO_2e per person from urban agriculture.

Ninety (90%) of the plant biomass consists of carbon, hydrogen, and oxygen, and photosynthetically reduced carbon products (photoassimilates) are transported from "sources, sites of production, to sinks, sites of growth and storage" [52]. Using the allometric equations, it is possible to estimate the carbon use efficiency (CUE) of plants. However, in doing so, there are some uncertainties because the CUE may vary based on plants and the surrounding environment. Therefore, often variations are expected between 15 and 20% for aboveground biomass. For the belowground biomass, however, the estimation varies between 20 and 50% of the aboveground biomass [53] because herbaceous plant species sequester less carbon depending upon the types of compost used, and deep-root plants sequester carbon based on the depth of soils and other conditions of the soil and root depth penetration. Ph% have concluded that the belowground biomass of plants is approximately 25% of the aboveground biomass; however, this may vary with rhizome plants [54] such as canna lilies, bearded iris, ginger and bamboo, and tuberous plants such as asparagus, airplane plant, dahlia, daylilies, peonies, some irises, sweet potato, taro, and many others. The productivity of plants varies based on the CUE. Assuming a high CUE at 85% and low CUE at 80, the aboveground biomass of plants is presented in Table 6.

Table 6. Aboveground and belowground production at high (85%) and low (80%) CUE for rhizome and tuberous plants. Belowground biomasses are estimated at 25% of the aboveground biomass. Fruit production is estimated at 40% CUE for rhizome plants and 25% for tuberous plants.

Plant Types	Aboveground Biomass (Tons)		Belowground Biomass (Tons)		Fruit Production (Tons)
	Minimum CUE	Maximum CUE	Minimum CUE	Maximum CUE	
Rhizome	209,920	223,040	52,480	55,760	104,960
Tuberous	183,680	196,800	49,920	49,200	12,300

The following calculation provides an estimate of the number of greenhouse gases that can be avoided by the practice of urban agriculture in Nepal.

(a) Total urban population in Nepal is approximately 19 million (66% of 29 m) (CBS, 2021).
(b) As an average household consists of 4.32 individuals, total no. of urban households is 19/4.32 = 4.4 million.
(c) Around 10% of households may be doubling up in the dwellings; thus, the estimated urban number of dwelling units = 3.96 m.
(d) Assuming 25% of the households live in multiunit complexes with limited balcony, rooftop, and ground spaces for farming, the total number of dwellings where urban farming is possible = 2.97 m (representing 12.8 m people) [50].
(e) Reference: 205 kg CO_2e per person avoidance due to urban agriculture in Madrid [50].

(f) In Nepal, let us assume 20.5 kg CO_2e per person avoidance (per capita/yr. emissions. This is based on the per-capita annual emission of 4.5 tons in Spain (2019), and for Nepal, 0.47 T (approx. 10% of Spain) (2019).
(g) If all urban residents practiced urban agriculture in Nepal, the total annual CO_2e avoidance = 262,400 T/yr.

On average, a person consumes about 590 g (0.000591 metric tons) of vegetables or fruits in a day. Nepali urban dwellers need 12.8 million~13 million × 0.000591 = 7683 metric tons of fruits or fruits a day. Annually, Nepali urban dwellers need 7683 × 365 = 2,804,295 tons. Nepal needs to adapt urban farming intensively in order to meet the gap of 2,607,495 tons under low CUE and 2,594,375 tons under high CUE.

5.3. Estimated Urban Food Production, and Contributions to Household Income

We can estimate the approximate acreage that can be used for urban agriculture in Nepal by making some simple assumptions, as follows:

(a) The total number of dwelling units (DU) 3.96. Section 5.2 c.
(b) Typical size of dwelling units = 90–150 square meters (average 120 square meters); 30 m^2 can be assigned to a dwelling unit (DU).
(c) Area available for urban farming on flat roofs (assuming half of the buildings have flat roofs) and that, on average, buildings are two stories and have balconies (typically 5 m^2/DU) and front/back/side yards (typically 5 m^2/DU) = 30 + 5 + 5 = 40 m^2.
(d) Assuming half of the available area is used for urban farming, each DU can use 20 m^2 for farming.
(e) Referring to Table 4 in Section 4, productivity per square meter of 3 kg of mixed typical vegetables (potato, beans, cabbage, fruits, etc.), the total production is 60 kg/growth cycle (3 times a year) = 778 kg/yr./household (an average household consists of 4.32 persons).
(f) The production per household = 778 kg/yr. It will be monetarily equivalent to approximately Rs 46,680/yr./household, assuming the average price of the typical vegetables to be Rs 60/kg in 2022. The prices are based on the price list published in major newspapers in Kathmandu. According to the 2022 exchange rate, this is approximately equal to USD 360 per year).
(g) Annual food expenditure per household in Nepal is Rs 144,330 (45% of 322,730)/yr.
(h) (USD 1206 in 2017) [49].
(i) Assuming a similar expenditure in 2022 and assuming any growth in expenditure and the rise of the dollar against Nepali Rupees can wash each other out, urban agriculture can provide 27% of a household's food expenditure.
(j) With the above assumptions, we can conservatively assume that urban agriculture can save a household 25% of its food expenditure.

6. Conclusions and Recommendations

Traditional agricultural and good supply systems have been facing two major problems. The food-growing process is energy-intensive, causing land, air, and water pollution. The supply chain from distant farmlands to urban areas is long and unpredictable, causing waste and adding to pollution and the emission of greenhouse gases. Urban farming with a distributed production that is close to the point of consumption can greatly help in supplementing the food needed by urban households. It can also help in reducing pollution, promoting healthy food, and mitigating some issues related to the food supply chain. Furthermore, it can also help reduce the emissions of greenhouse gases, help urban households save money on food, and sometimes make money by commercializing small household urban farming.

Urban farming can be supported by a public-private partnership (PPP), where public institutions can assist individual households in technology, training, and the marketing of their products. The agriculture extension programs of many universities in the United States are a great example of how public research can support urban farming.

It is recommended that the local authorities and institutions in Nepal support urban farmers with technology, marketing, training, and appropriate policies. The municipal governments can create helpful regulations in zoning and land use to promote urban farming while protecting public health and safety. They can also facilitate the creation of urban farmers' markets for households who produce extra food and wish to sell it. Though urban farming has been much advocated recently, the building codes should also foresee potential urban farming on terraces, on-site, balconies, and rooftops and ensure that waterproofing and load bearing for the additional soil, water, and plants is included in the calculation required for the structure of buildings.

Urban farming is relevant for rapidly urbanizing Nepal. Nepal's census records show that over 66% of the total population of Nepal lives in urban areas. However, many of these urban classified areas have rural settings, making Nepal a "ruralopolis". Though many recent rural areas are defined as urban, these newly created towns have plenty of agricultural lands within their territories. These farmlands can offer the best ecosystems for urban farming in or around urban and peri-urban areas to produce food to meet the needs of the family and to their traditional customers.

To make the best use of opportunities provided by urban farming, appropriate and enabling policies related to planning practice, and zoning ordinances, comprehensive plans need to be developed. This will be a good PPP practice. Similarly, urban agriculture studies and the promotion of "foodsheds" (such as watersheds) for urban population groups can help to advance urban agriculture.

Author Contributions: K.B., theoretical discussion, data gathering and analysis, and preparing all the figures; A.P.A., theoretical issues and conceptual framework, organization of the contents, comparative studies between Arizona and Nepal, the literature review, and incorporation of different arguments. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Any data used in the study can be requested from the author.

Acknowledgments: Anonymous reviewers who helped in improving this paper.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Variables used in the linear regression models for years 2017, 2018, 2019, 2020 and 2021 include:

1. Urban_17, Urban_18, Urban_19, Urban_20, and Urban_2021: This represents the urban built-up area with impervious surface, buildings of various types, and built-up areas in and around houses. Independent variables include the following:
2. Agri_17, Agri_18, Agri_19, Agri_20, and Agri_21: Agricultural areas used to grow various crops. These areas are located within the urban territories in hectares.
3. Forest_17, Forest_18, Forest_19, Forest_20, and Forest_21: Forest areas located within the urban territories in hectares. These are the forested areas where the crown cover is over 25%. This area contains forest trees with boles and dense crowns.
4. Shrub_17, Shrub_18, Shrub_19, Shrub_20, and Shrub_21: Shrublands are areas located within the urban territories in hectares. These include forested areas where the canopy cover is less than 20% and most of the vegetation is in the form of shrubs and bushes.

$$Y = \beta 0 + \beta 1 x1 + \beta 2 x2 + \cdots \ldots \beta i n i + \varepsilon$$

where $\beta 0$ = constant, $\beta 1$ = Coefficient for $x1$, $\beta_i\ n_i$ = coefficients for independent variables, and ε = error terms.

Table A1. Regression model for 2017.

Regression Statistics								
Multiple R	0.278981							
R Square	0.07783							
Adjusted R Square	0.077043							
Standard Error	76.70347							
Observations	3519							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	3	1,745,391	581,797.1	98.88753	1.89×10^{-61}			
Residual	3515	20,680,230	5883.423					
Total	3518	22,425,622						
	Coefficients	*Standard Error*	*t Stat*	*p-Value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	70.26339	1.927585	36.45152	4.7×10^{-247}	66.4841	74.04269	66.4841	74.04269
Forest_17	−0.00503	0.001335	−3.76468	0.000169	−0.00764	−0.00241	−0.00764	−0.00241
Agri_17	0.031981	0.003947	8.101709	7.4×10^{-16}	0.024242	0.039721	0.024242	0.039721
Shrub_17	−0.02359	0.002356	−10.014	2.71×10^{-23}	−0.02821	−0.01897	−0.02821	−0.01897

Table A2. Regression model for 2018.

Regression Statistics								
Multiple R	0.303474							
R Square	0.092097							
Adjusted R Square	0.091322							
Standard Error	81.10883							
Observations	3519							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	3	2,345,666	781,888.7	118.8526	2.59×10^{-73}			
Residual	3515	23,123,929	6578.643					
Total	3518	25,469,595						
	Coefficients	*Standard Error*	*t Stat*	*p-Value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	74.1408	2.030604	36.51171	9.5×10^{-248}	70.15952	78.12208	70.15952	78.12208
Forest_18	−0.00371	0.001439	−2.57671	0.010015	−0.00653	−0.00089	−0.00653	−0.00089
Agri_18	0.039802	0.004162	9.563283	2.07×10^{-21}	0.031642	0.047962	0.031642	0.047962
Shrub_18	−0.02717	0.002424	−11.2104	1.11×10^{-28}	−0.03193	−0.02242	−0.03193	−0.02242

Table A3. Regression model for 2019.

Regression Statistics								
Multiple R	0.289235							
R Square	0.083657							
Adjusted R Square	0.082875							
Standard Error	86.1838							
Observations	3519							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	3	2,383,528	794,509.2	106.9665	2.85×10^{-66}			
Residual	3515	26,108,183	7427.648					
Total	3518	28,491,711						
	Coefficients	*Standard Error*	*t Stat*	*p-Value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	79.5192	2.152556	36.94176	1×10^{-252}	75.29882	83.73959	75.29882	83.73959
Forest_19	−0.00204	0.00163	−1.24904	0.211732	−0.00523	0.00116	−0.00523	0.00116
Agri_19	0.03904	0.004404	8.864118	1.2×10^{-18}	0.030404	0.047675	0.030404	0.047675
Shrub_19	−0.02981	0.002714	−10.986	1.25×10^{-27}	−0.03513	−0.02449	−0.03513	−0.02449

Table A4. Regression model for 2020.

Regression Statistics								
Multiple R	0.296757							
R Square	0.088065							
Adjusted R Square	0.087286							
Standard Error	91.96224							
Observations	3519							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	3	2,870,657	956,885.6	113.1464	6.1×10^{-70}			
Residual	3515	29,726,545	8457.054					
Total	3518	32,597,201						
	Coefficients	*Standard Error*	*t Stat*	*p-Value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	85.74272	2.289378	37.45241	1.2×10^{-258}	81.25408	90.23137	81.25408	90.23137
Forest_20	−0.00206	0.001562	−1.31951	0.187085	−0.00512	0.001001	−0.00512	0.001001
Agril_20	0.052424	0.00484	10.83071	6.52×10^{-27}	0.042934	0.061914	0.042934	0.061914
Shrub_20	−0.0306	0.002895	−10.5701	9.93×10^{-26}	−0.03628	−0.02493	−0.03628	−0.02493

Table A5. Regression model for 2021.

Regression Statistics								
Multiple R	0.334757							
R Square	0.112062							
Adjusted R Square	0.111304							
Standard Error	92.26975							
Observations	3519							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	3	3,776,762	1,258,921	147.8699	3.04×10^{-90}			
Residual	3515	29,925,676	8513.706					
Total	3518	33,702,438						
	Coefficients	*Standard Error*	*t Stat*	*p-Value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	84.84215	2.286997	37.09761	1.6×10^{-254}	80.35817	89.32612	80.35817	89.32612
Forest_21	−0.00303	0.001611	−1.88285	0.059804	−0.00619	0.000125	−0.00619	0.000125
Agri_21	0.059594	0.004865	12.24934	8.21×10^{-34}	0.050055	0.069133	0.050055	0.069133
Shrub_21	−0.03217	0.002725	−11.8081	1.39×10^{-31}	−0.03751	−0.02683	−0.03751	−0.02683

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