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Exploring land use scenarios in metropolitan areas: food balance in a local agricultural system by using a multi-objective optimization model

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Abstract

The assessment of sustainability of agro-food systems is based on different and several tools. However, economic and policy implications of structural changes, such as land use change, and other modifications, for instance a different orientation or farming technique, could be mainly determined through scenario analysis. Especially in metropolitan regions, where the agricultural sector is threatened by various different pressures, a food supply adequately respondent to the demand is needed. In this sense the paper proposes the utilization of mathematical programming to assess some possible scenarios related to a higher compliance between food supply and demand. The approach is based on a linear programming model that takes into account the production and consumption dimensions in the Milan Metropolitan Area. Five scenarios are simulated, with different levels of sustainability and compliance with demand, demonstrating the potentialities of the regional agro-food system in adapting and adjusting itself to such modifications.

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Keywords: metropolitan area; land use; scenario analysis; optimization models.

1. Introduction

The interest in issues related to urban food supply is not something new. Major efforts are addressed to deepen this topic in Developing Countries, where the main problem concerns with the necessity to increase and improve

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food security (Gallaher et al., 2013). However, the theme is continuously on the rise in Developed Countries, as well. In these contexts it in fact emerges as a sustainability issue: on one hand the enhancement of productivity is needed to provide high quality food to an increasing number of people (UNDESA, 2012), on the other hand modifications in agricultural practices are required to ensure more sustainable and environmental-friendly activities.

Literature variously deepens the role of urban and peri-urban agriculture in providing food to cities and urban conglomerations, estimating at what extent it is able to do this. In other words, several authors analyzed the food self-reliance of an urban area, as the capacity to produce with its own resources and within its physical boundaries (Morris, 1987) and even beyond, enough food for people living there (Mok, 2014) fulfilling their food demand (Timmons et al., 2008). In this theoretical framework, the key role is of the analysis of both food demand and supply dimension. This should be tackled under different profiles, considering the importance of food, the role of producers and consumers and the structural features of the system, such as land use patterns.

In the context of Agro-food Systems, consumers are playing a more and more important role and their preferences and perceptions have been leading to the rise of alternative systems, possibly often defined by a spatial proximity between producers and consumers, in "*a critical process of reconnection*" (Ilbery et al., 2005, p. 117) that involves even sociological and political aspects (Hinrichs, 2000; Qazi and Selfa, 2005): the so-called Local Agro-food Systems (Feenstra, 1997; Henderson, 1998; Lacy, 2000; Hinrichs, 2003) and Alternative Agro-Food Networks (Murdoch et al. 2000; Renting et al. 2003), which variously contribute to the development and the strengthening of local supply chains and environmental-friendly networks that pay attention to social inclusion and favour local value added (Berry, 1977, Barham et al., 2005, Pirog, 2003). In fact, as demonstrated by the increasing interest in food planning initiatives promoted in several cities and metropolitan areas, food is an urban issue affecting the local economy, the environment, the public health and the quality of neighbourhoods (Pothukuchi and Kaufman, 1999). The management of urban food systems in fact involves i) the social dimension, for instance the aid interventions to poor families through the distribution of free meals, ii) the economic aspect, with impacts not only on the local agricultural sector but also on the sustainable management of green areas, and iii) the environment, through water management and conservation of green areas and biodiversity.

The sustainable use of local resources, as long as the preservation of environmental-valued elements in strongly-urbanized areas, cannot therefore ignore the features of the agricultural system. Any political intervention in the food sector or any food planning initiative should be based on the knowledge of the agricultural system they operate and can impact on. A first characterization of an agro-food system concerns with the quantitative dimension of food demand - i.e. the consumption - and supply - the primary production-, as the steps at the extremes of any food chain. The amount of demanded food depends on specific dietary pattern and finally affects total regional consumptions in combination with the population size of the area, which is the most driving factor in determining food needs within a territory. On the other hand, the capacity of the system in providing food and meeting demand varies according to the suitability of the territory itself and the specialization of the primary sector, or in more general terms, on available agricultural area and land use. In this sense the maintenance of local peri-urban and proximity agriculture is a fundamental aim. This would also favour the spatial reconnection between local food demand and supply, creating the bases for the development of innovative local agro-food chains and metropolitan agro-food models.

Preliminary analyses and assessments of the context are essential. They play a role as instruments for providing indications on the potentialities of the system and on their strengths and weaknesses, finally allowing to assess the possibilities of an effective reconnection and to shape proper regulations according to the actual conditions and the needs of the territory. In order to do this, adequate analysis tools are needed. In this sense the paper proposes a methodology for the analysis of an agro-food system in a metropolitan context. The analytical tool adopted refers to mathematical programming, and linear programming in particular. Such a model is adopted to simulate the response of the potentialities of the agricultural system in the Milan metropolitan region, under different scenarios, related to structural and external modifications and aimed at assess the optimal crop land use allocation that ensures the highest compliance of food production with consumption.

1.1. The case study: Milan metropolitan area

The Milan Metropolitan Area (MMA) is one of the most populated in Europe and ranks first in Italy (OECD, 2006). The region in fact encompasses a large part of Lombardy region (figures 1 and 2), covering more than 301,000 km^2 with a population of about 7.8 million people.

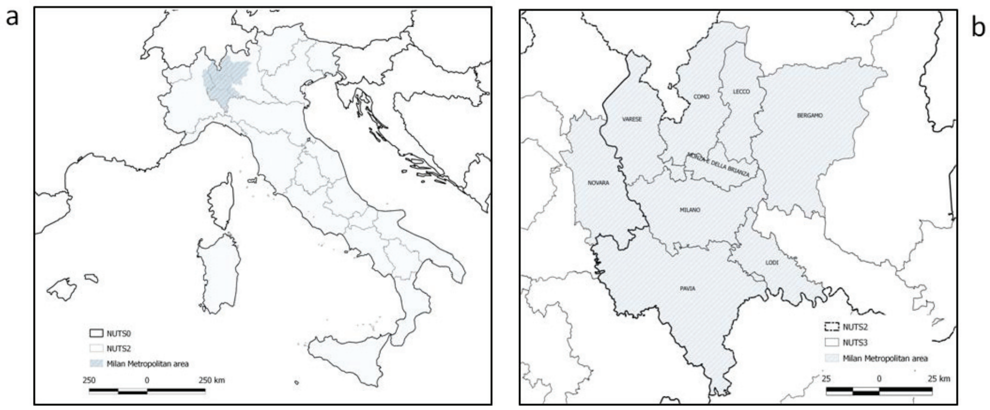

Fig. 1. (a) location of MMA; (b) NUTS3 encompassed in the MMA.

Provinces included in the spatial delimitation of the area gravitate on the city of Milan, which represents the main fulcrum of the area itself and extends its influence far beyond its administrative boundaries. This macro-area is however characterized by the polycentric structure of urban settlements (Zasada et al., 2013), with the coexistence and the interaction between elements with different territorial and demographic characteristics and dynamics (Sali et al., 2014). In particular, along with high-densely populated areas around Milan and in the Northern part of the region, more rural areas where agricultural practices are still deep-rooted can be found. The intensive agriculture of the Southern part of the MMA is highly oriented to cereal cultivation and livestock breeding (table 1): if one hand areas intended for maize and rice account for most of their extent at national level, on the other hand the more scarce amount of land intended for horticultural products ensures produced amounts comparable to rice. Moreover, it must be pointed out that the breeding sector is a very important regional activity, especially for what concerns the dairy sector: milk productions can meet the market demand for dairy products in the area itself (Corsi et al., 2015).

Despite the prominent role played by the agricultural sector, in recent years the region has been more and more subjected to a strong aggressive urbanization that represents the major threat to the system (Mazzocchi et al., 2013); at the same time, the diminishment of arable land (Oldeman et al., 1991) has repercussion on the productive potentials of the system itself. The maintenance and the conservation of agricultural areas, especially in the peri-urban context, should be then promoted as a strategy to contrast urban sprawl and its correlated effects on the rural territory.

Table 1. Main features of case study area

Feature		MMA	Italy	% of national total
Land size (km^2)		25,200	301,340	8.36
Population (Mio. people)		7.89	59.43	13.28
Density (people/km^2)		602	197	
GDP (thousand USD)		35.6	206.9	17.21
Workers in agriculture (n.)		55,265	3,628,208	1.5
UAA (ha)		490,668	12,782,936	3.84
of which	*fruit*	1,596		0.29
	wheat	44,446		2.27
	barley	2,294		0.88
	oats	77		0.05
	maize	2,153		24.19
	rice	140,190		57.03
	vegetables	4,533		1.51
	pulses	1,042		0.75
	potatoes	380		1.40
	olives for oil	425		0.04
	other oil plants	3,341		1.10
	wine grapes	15,024		2.26
	sugar beet	6,895		11.76
	maize for feed	109,362		24.18
	temporary grassland	39,030		2.04
	permanent grassland	87,732		2.55
UAA (ha per capita)		0.062	0.047	
Number of farms (n.)		26,289		1.62
Farm dimension (ha/farm)		18.6	7.89	
Animal numerousness (heads)	*dairy cows*	172,644		23.50
	beef cattle	786,060		59.67
	pigs	2,279,849		26.57
	broilers	1,322,993		3.01
	layers	2,756,754		15.30

Authors' elaborations on OECD, 2006; ISTAT, 2010; ISTAT, 2011; Corsi et al., 2015.

2. Methodology

In the assessment of the sustainability of agro-food systems, various tools could be used in the analysis of the system itself under different conditions. From an economic perspective, deepening the performance in different scenarios also means the evaluation of the consequences structural and external modifications, from land use change to a different productive orientation or farming technique, may have on the system and its potentialities. Simulation models are a valid solution to tackle this issue, and in this sense Linear Programming is a suitable option.

The paper proposes the application of such kind of models to the case study area, deepening the capacities of the agricultural productive structure in meeting population food demand, according to possible changes on both the demand and the supply side. This results in a methodological path consisting of the following steps:

- Quantification of local food demand and supply at staple-food level. With regard to food demand analysis consumptions expressed by dietary habits (*EFSA, 2011*) have been back transformed to the consumed amounts of their correspondent agricultural primary product. On the supply side, productions arise from the combination of National data (*ISTAT, 2010*) regarding land extent and yields or, for animal productions, animal heads, productivity per head and the local productive potential of forages to feed livestock. Both dimensions can be differently described, as shown in table 2;
- Modelling the relationship between supply and demand (de facto) by a multi-objective model that measures the gap between the amounts consumed and the quantities produced of each staple food category;
- Assessment of adaptations and adjustments of the agricultural production system to a closer compliance with food demand, through the modelling of different scenarios of production or consumption patterns.

Table 2. features of food demand and consumption patterns in the area.

Staple food	**Quantities (t/year)**		**Calories (.000 kcal)**		**Production value (Mio. EUR)**	
	Demand	**Supply**	**Demand**	**Supply**	**Demand**	**Supply**
Fruit	480,641	10,182	374,899,943	7,941,746	495,060	10,487
Wheat	662,370	137,048	2,338,166,704	483,777,958	157,313	32,549
Barley	22,457	11,799	87,588,086	37,637,551	5,718	2,457
Oats	1,588	253	5,924,086	944,540	325	52
Maize	1,588	24,619	5,733,499	88,876,150	315	4,889
Rice	77,791	507,720	248,932,523	1,624,705,182	28,213	184,135
Other cereals	17,195	34,686	59,358,272	119,734,801	4167	8,405
Vegetables	490,376	121,855	142,209,050	35,338,035	328,552	81,643
Pulses	27,401	2,824	80,285,395	8,273,064	38,362	3,953
Potatoes	145,632	10,897	215,535,548	16,127,450	55,340	4,141
Olives for oil and other oil plants	648,230	990	922,536,805	2,147,748	511,170	383
Wine grapes	265,937	78,901	194,134,142	57,597,623	116,480	34,559
Sugar beet	452,475	31,262	261,088,987	18,038,909	18,099	1,250
Milk	2,484,961	1,964,603	1,202,720,957	950,867,844	991,748	784,073
Beef meat	168,997	1,498	221,386,089	1,961,791	663,917	5,883
Pig meat	79,411	149,348	228,703,749	430,122,361	116,734	219,542
Poultry meat	60,021	4,889	84,629,331	6,893,891	73,225	5,965
Eggs	53,937	67,718	69,039,621	86,679,677	116,864	146,723

2.1. The formal model and general constraints

In particular, the multi-objective model presented as the objective function, aims at minimizing the sum of the differences that each staple food shows between its own levels of production and consumption.

In this way, given D_i and S_i respectively the demanded and the supplied amounts of each i primary product, the production itself is defined as a function of the productive factor *x to* be determined through the model (land extent, animal numerousness or amounts of animal products)

$$S_i = S_i(x), \quad (1)$$

where the function $S_i(x)$ in turn depends on the relation between crop production (productive yield or productivity per head) and its processing needed to obtain the i primary product, i.e. processing or slaughtering yield, fodder units produced by the f fodder crop and consumed by animals and converted into animal products.

The implemented multi-objective model is expressed in the form:

Minimize $\sum_i w_i|D_i - S_i(x)|$ (2)

subject to $Ax \leq c$ (3)

and $x \geq 0,$ (4)

where x represents the vector of the unknown variables that will be determined through the model, c the vector of coefficients used in the function, A the (known) matrix of coefficients and the w the importance given to each primary product i to meet the respective food demand. The values of the variables included in this latter vector is set equal to 1, due to the homogenous distances and the consistence in terms of unit of measure.
Some of the constraints expressed by eq. 3 still have validity across all simulated scenarios. In particular, to the model they are imposed:

- land constraints, ensuring that no more land than the available is used

$$\sum_i x_i + \sum_f x_f = \sum_i land_i + \sum_f land_f \quad (5)$$

with $land_i$ and $land_f$ current land extents of the i primary products and the f fodder crops respectively, and imposing the maintenance of areas intended for permanent crops:

$$x_i = land_i \; if \; i = \text{winegrapes"} \; or \; \text{"}olive\;for\;oil\text{"} \quad (6)$$

$$x_f = land_f \; if \; f = \text{"}permanent\;grassland\text{"} \quad (7)$$

- fodder units balance, ensuring that all fodder units provided by foragers are consumed by animals:

$$\sum_f fu_f * x_f - \sum_a dfu_a * x_a = 0, \quad (8)$$

where fu is the amount of fodder units per hectare of the f fodder crop and dfu the amount of fodder units consumed by the a animal.

- balance for animal productions:

$$x_a - ly_p * x_p = 0, \quad (9)$$

where ly is the number of animals to produce a unit of the p animal products.

2.2. Simulated scenarios and specific constraints

The optimization model could be used not only to hypothesize the redistribution of internal resources to optimize the compliance of food supply with the demand. A recalibration of the imposed constraints can play a role in providing information. For instance, considering current and proposed agribusiness policies to support the local agricultural system, it would be possible to simulate plausible scenarios that could become useful tools to support policy-makers towards the improvement of sustainability in the agro-food system. The scenarios introduced in this paper operate in this sense, being related to different ways for improving sustainability through the increase of the reconnection – variously expressed - between local demand and local supply.

The conditions simulated and assessed are traced hereinafter.

- Scenario 0: the baseline scenario, in which current agricultural productions are compared to a positive demand for food, describing the features of the regional agricultural system, in terms of both cultivated crops and livestock numerousness;

- Scenario 1: this scenario focuses on minimizing the gap between demand and supply, returning how the production system could be adapted in order to satisfy as much as possible the demand of each staple food. The specific constrain affecting this simulation ensures sufficient quantities of crop and animal productions to meet the respective food demand, without overproductions:

$$S_i(x) = D_i \quad (10)$$

$$S_p(x) = D_p \quad (11)$$

- Scenario 2. The strong presence of livestock in the region requires a large amount of fodder and fodder crops, which is currently locally supplied for only 30%; due to this condition, the scenario aims to assess the consequences that the hypothesis of producing locally the whole fodder need could have on the capability of agricultural production system in complying with food demand. For this reason the inputs related to fodder needs vary according to this, *ceteris paribus* the conditions set in the previous scenario.

- Scenario 3. The hypothesis of converting the agricultural system towards practices that satisfy a vegetarian diet is made: this allows returning the most cost-effective solution able to replace meat proteins with those provided by legumes, milk and eggs:

$$\sum_i (cal_i * x_i) + \sum_p (cal_p * x_p) = DC \quad (12)$$

  where cal_i and cal_p are respectively the calories provided by the amounts of the i primary product and the p product of animal origin and DC the calories demanded through the dietary pattern.

- Scenario 4 finally represents a more rigorous condition, where animal proteins are forbidden. The scenario hypothesizes the adaptation of the agricultural system to food needs and demand expressed by vegan consumers; similarly to the previous simulation, legumes only replace all the animal proteins:

$$\sum_i (cal_i * x_i) = DC \quad (13)$$

3. Results and discussion

The baseline scenario represents an overview of the current agricultural system in terms of cultivated crops and livestock numerousness, and this is mainly useful for comparison with others simulations. The scenario describes the features of the metropolitan agricultural system, revealing that it is mainly based on cereals (especially rice) and fodder cultivation, this latter to feed the high number of animal bred for both dairy and meat productions (table 3). This result in a scarce compliance with other food crops less cultivated, finally leading to an overall inadequate compliance with the dietary pattern. In fact, the minimization of the distance between demand and supply, modelled in the first scenario, would require increased areas for all food crops, except for those which productions already exceed demanded amounts, i.e. rice. With regard to fodder crops, a redistribution of areas among maize and temporary grasslands occurs. This also results, with more pronounced modifications, in the numerousness of animal bred: an increase in dairy cows and layers and even strongly in the number of broilers is evident, along with a marked decrease in pig heads, historically one of the most spread animal breeding in the area. Such a scenario has repercussions on the total value of the production: the variation in livestock heads causes in fact a diminution in the value of about 200 Million Euro.

Under the hypothesis of a complete self-reliance in fodder crops (scenario 2), areas of food crops encounter the same redistribution observed in scenario 1; the cultivation of temporary grasslands is not encouraged at all, in favour of permanent meadows and especially grain maize for feed. Such production can sustain all animal breeding, except beef cattle; at the same time, similarly to the previous scenario, pig heads would strongly decrease. Though the profitability of fodder maize, the reduced number of animals leads to a further decrease in the total production value, either in comparison with the baseline (-24%) and scenario 1 (-19%).

It is certainly not a coincidence that these scenarios returns an economic value of production lower than the baseline. What it is currently produced results from the laborious process of adaptation to the global economic environment, in order to take advantage of the competitive factors of which the regional agricultural system is equipped. This has then led to a specialization in the productions which modification necessarily implies a reduction of the generated value.

Scenarios 3 and 4 are related to a change in the demand, expressed by the modification in consumers' dietary habits. In the former case, where compliance with a vegetarian diet is needed, results of the model general indicate increased crop productions, except for rice and maize for both food and feed: among them the highest augmentation is related to pulses, which cultivation can rely on more than 90.000 ha. This ensures a fairly good overall correspondence with the food demand. Concerning animal productions, a twofold augmentation in the number of dairy cows occurs, while layers are subjected to an increase of an order of magnitude, finally resulting in a complete self-sufficiency for allowed animal products, consistently with the initial condition of vegetarian needs. Thus, the despite lower income provided by food crops than by feed or animal products, the total economic value generated, due to the large amounts of milk and eggs, it is higher than the current one (+ 122%).

With the vegan scenario, areas of temporary forages are redistributed among other land uses. The cultivation of minor cereals, such as barley and oats, and oil plants is not favoured; as long as the strong reduction in rice cultivation, the most part of agricultural area for food (70%) is devoted to pulses. In this condition the compliance with food demand is on an optimal level: on one hand food crop productions allow quantitative surplus, except in the case of olives for oil and wine grapes, while on the other hand, the system adapts itself to the demand, not returning any area devoted to feed crops and consequently not permitting animal breeding. This situation leads to a reduction in the value generated: in comparison to the current potentialities it decreases from 3 to 2 billion Euro (-69%) and such kind of trend is shown also in comparison to the vegetarian scenario, with a reduction of 38%, mostly due to the absence of products of animal origin.

Different production values are due to implications not immediately evident from the comparison of the values themselves. In fact, though the lower economic balances of scenarios 0, 1 and 2, it must be considered that the former production patterns include a range of processed foods. This way, the processing itself can contribute in increasing the agricultural value generated in the territory, by generating further value added: in these cases the economic balance returned by simulations can potentially increase due to this condition. Conversely, more limited amounts of foods to be processed, or even their total lack, as in the vegetarian and in the vegan productive system respectively, would scarcely generate further value, finally resulting in the actual potentialities of the system.

Table 3. Results of simulated scenarios.

Agricultural land use and animal breeding	Scenario 0 (baseline)	Scenario 1 (minimum gap)	Scenario 2 (100% fodder)	Scenario 3 (Vegetarian)	Scenario 4 (Vegan)
Crop area (ha)					
Total available land	*458,518*	*458,518*	*458,518*	*458,518*	*458,518*
Fruit	1,596	40,053	40,053	40,053	40,053
Wheat	44,446	122,661	122,661	122,661	13,096
Barley	2,294	5,708	5,708	5,708	
Oats	77	478	478	478	
Maize	2,153	155	155	155	155
Rice	140,190	10,297	10,297	10,297	10,297
Vegetables (open field)	3,668	13,658	13,685	13,658	13,658
Vegetables (protected)	865	3,221	3,221	3,221	3,221
Pulses	1,042	9,134	9,134	90,122	250,223
Potatoes	380	5,201	5,201	5,201	5,201
Olives for oil	425	425	425	425	425
Oil plants	3,341	4,633	4,633	4,633	
Wine grapes	15,024	15,024	15,024	15,024	15,024
Sugar beet	6,895	9,432	9,432	9,432	9,432
Maize for feed	109,362	67,443	130,706	49,718	
Temporary grassland	39,030	63,264			
Permanent grassland	87,732	87,732	87,732	87,732	87,732
Animal numerousness (heads)					
Dairy cows	172,644	278,583	278,583	278,583	
Beef cattle	786,060	602,646			
Pigs	2,279,849	241,930	201,510		
Broilers	1,322,993	13,248,520	4,319,331		
Layers	2,756,754	3,154,211	3,154,211	22,959,140	
Value of production (Mio, EUR)	*3,015*	*2,813*	*2,289*	*3,362*	*2,081*

It must be reminded that this kind of approach aims to assess the potentialities of the agro-food system in a metropolitan area in adequately responding to its own food demand. It is quite obvious as well that in strongly urbanized contexts such performances are poor, due to exiguous availability of agricultural and the high food demand expressed by population, This scarce capability is instead balanced by market dynamics and national and international trade in food products, which however don’t allow seizing the actual potentialities of the agro-food system. It is also clear that the potentialities themselves depend on the regional features of the system under analysis, from agro-climate characteristics to land suitability and cultural aspects. These peculiarities must be taken into account whenever adopting a simulation model, in order to consider plausible scenarios for the case study area, as well as when conclusions are drawn. In fact, as the results have demonstrated under changes on dietary habits, interventions suggested represent a radical choice that certainly affects, far beyond economic results, the system as a whole, requiring profound structural modifications with strong consequences and repercussions on the agro-food sector. This is not the focus of the paper, but such considerations should be contemplate for a better characterization of system potentialities and sustainability.

The adoption of linear programming has allowed to create a theoretical and methodological framework that can be applied to any other case study area or territorial aggregations. It must be pointed out that further analyses (Sali et al., 2015) have been allowing the assessment of agro-food systems in different European metropolitan areas and the quanti-qualitative description of their productive and supplying capacities. In this sense, preliminary results demonstrate an incomplete fulfilment of dietary needs either in other urban contexts: two of them are similar to the case study area for agricultural area extent and policentricity of urban settlements – the Rotterdam metropolitan region -, and for population numerousness, i.e. Berlin-Brandenburg. Despite strong demographic and territorial differences they have in common the sustainment of the demand only for few food categories and not for the diet as a whole, finally revealing the specialization of the primary sector in the areas. These analyses describe the different compliance with food requirements and indicate a diversified agricultural production across considered regions: in the Dutch case most of agricultural productions are intended for milk and dairy products, fruits and vegetables and sugar beets satisfying their respective demand; produced amounts in Berlin are more diversified, encompassing cereals, oil plants, and meat, too, but with a level of food self-reliance similar to that of the Rotterdam area. Such an approach reflects the quantitative dimension of food demand and supply which constitutes the first step for the implementation of the proposed linear programming model; in fact, the interpretation of results indicates the possibility to run the model in these contexts, as well, where chances to reconnect demanded and supplied amounts can be deepened.

4. Conclusions

The utilization of linear programming model has revealed a relatively simply approach to simulate modifications in the regional demand pattern. For a more comprehensive analysis of the system, results should however be discussed taking into account the effective and practical feasibility of suggested indications; the deterministic nature of the model leads to assess the potentialities of the system only, without providing insights on the consequences at a wider level the application of optimal allocation would have.

Thus, the modeling has demonstrate the role of such approach in assessing the capacities of system to adapt to structural changes and external factors; in this way the simulations have shown the role of the modeling itself in deepening the possibility to maintain agricultural areas close to the city, as a strategy for strengthening peri-urban agriculture and the metropolitan system as a whole. This could be strategic not only in economic terms, but also from the point of view of farms' resilience, which number has been reducing (ISTAT, 2010), and a political perspective, providing useful indications for food-related policies and regulations for the agricultural and landscape sector.

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