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Ample room for reducing agrochemical inputs without productivity loss: The case of vegetable production in Uruguay

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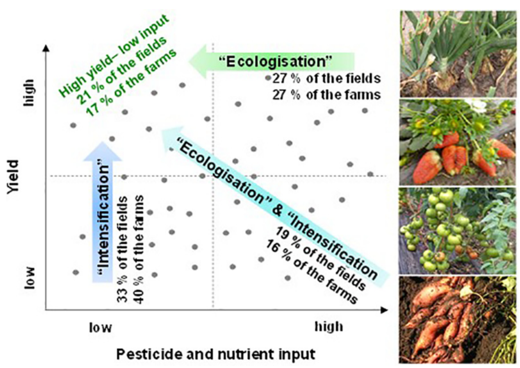
HIGHLIGHTS

- Relations between pesticide and nutrient inputs and yields evaluated for 5 crops
- No or weak relations between input use and yields
- Input use not related to agronomic criteria or farm resource endowment
- Several cases stood out by reaching high yields and low input levels.
- Results show the need and opportunities for transitions to more sustainable states.

GRAPHICAL ABSTRACT



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ABSTRACT

Vegetables are commonly produced with high inputs of pesticides and fertilisers to boost production and meet cosmetic market standards. Yet, reports on the relationships between agrochemical inputs and crop productivity are scattered and an overview is missing. We assessed the relationship between pesticide and nutrient inputs and crop productivity for five vegetable crops in the south of Uruguay at field and farm level and explored the relation with farm resource endowment. We analysed crop yield and input use for tomato, onion, sweet potato, and strawberry with a dataset of 82 farms and 428 fields constructed between 2012 and 2017. Clear crop-specific patterns in pesticide and nutrient input levels were found, despite considerable variation across fields within the same crop. Strawberry and long cycle tomato had the greatest pesticide input regarding of the number of applications (20 and 18, respectively) and pesticide load (21 kg AI ha^{-1}). Cumulative nutrient inputs were greatest for long cycle tomato (1127 kg ha^{-1}). The relationships between inputs and yield were weak or non-significant, indicating inefficiencies and overuse of inputs, and there was no agronomical rationale for input use. We found substantial variation in management practices between fields and farms. In several cases, 21% of the fields and 17% of the farms producing onion, strawberry and tomato, attained relatively high yield levels with limited input levels. Yield and input use levels were not related to farm resource endowment. Our findings question the efficiency of the current high levels of pesticide and nutrient inputs in Uruguayan vegetable systems. The inputs may pose environmental and human health risks and in most cases did not increase yields. Learning from positive deviant farmers in combination with guided farm redesign, high-quality extension services, and use of context-specific knowledge and technologies may equip farmers to use more sustainable management practices.

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1. Introduction

Closing yield gaps while decreasing pesticide and fertiliser use is a major challenge for increasing the sustainability of production systems. Feeding a growing world population has been the main argument to promote a high-input industrial agriculture model, promising high crop yields. Although this strategy has boosted agricultural production, it has also negatively impacted human health and the environment (FAO, 2017; UNCTAD, 2017). For instance, the copious use of synthetic pesticides and artificial fertilisers has been found to contaminate and degrade the environment, pose human health hazards, and reduce the nutritional value of food (Mahmood et al., 2016; Tittonell et al., 2016; UNCTAD, 2017). Therefore, the industrial agriculture model is under scrutiny, and its viability and desirability are increasingly questioned (IPBES, 2019; Tittonell et al., 2016).

The industrial production model was introduced in Uruguay in the 1970s and, over time, became adopted in large-scale grain cropping (Baraibar Norberg, 2020; Ernst et al., 2016; Gazzano and Gómez Perazzoli, 2017) as well as in vegetable production. Even though vegetable production is concentrated on a relatively small fraction of Uruguay's agricultural area, it generates a substantial environmental impact. The high input of pesticides and synthetic fertilisers, among other management practices, in intensively managed vegetable farms has contributed to soil degradation (Alliaume et al., 2013; Dogliotti et al., 2014), water pollution (Barreto et al., 2017), biodiversity loss (MVOTMA, 2016), and human health hazards (Burger, 2013). These concerns have been expressed by researchers, farmers, consumers, and society in general (Blum et al., 2006; CEUTA, 2006; Chiappe et al., 2003; CNFR, 2016, 2017). Farmers have experienced a lack of yield responses despite high pesticide and synthetic fertiliser inputs, and resistance development in pest populations are common, triggering even greater pesticide use. Therefore, the industrial model of vegetable production and the associated adverse side effects jeopardise the long-term sustainability and productivity of vegetable production in Uruguay.

Concerns about the impacts of the industrial agriculture model have sparked interest in agroecology (Altieri, 2002) and ecological intensification (Tittonell, 2014) around the world (FAO, 2015; UNCTAD, 2017) and also in Uruguay (Poder Legislativo ROU, 2018). These approaches aim to maintain or increase production supported by ecological processes, reducing external input use, and minimising negative impacts on the environment and society. Agroecology is based on principles revolving around recycling, efficiency, diversity, regulation, and synergies promoting ecological processes (Tittonell, 2015). However, while there is increasing interest in agroecology, the principles and transition strategies are often too general to be directly translated into concrete designs and context-specific management practices (Altieri, 2002; Duru et al., 2015). Even in a particular context, specific pathways may be needed for different farming systems.

Reducing agrochemical inputs is a crucial agroecological principle (Altieri, 2002) often related with the first steps of agroecological transitions (Gliessman, 2015). Although vegetable production is usually associated with extensive use of pesticides and fertilisers to boost production and meet cosmetic market standards, there is considerable variability among farms in their management and in the associated input use efficiencies and crop performances (Abunyuwah et al., 2020; Ahovi et al., 2021; Lechenet et al., 2016). Farmers make their crop management decisions within the realm of their production situations, i.e., the physical, biological, technical, social, and economic context in which production occurs (Savary et al., 2006), and their decisions, in turn, shape their production situations. As a result, systems that evolved based on higher or lower input use may require different strategies for an agroecological transition. Farms with high productivity and high input use may follow an "ecologisation" strategy to reduce inputs while maintaining productivity. In contrast, farms with low productivity and low input use may follow an "ecological intensification" strategy as an affordable and sustainable way to increase productivity at the same or lower levels of inputs (Tittonell et al., 2016).

Insight into the relationships between the types and levels of inputs and the performance and productivity of farming systems is essential to inform the design of appropriate agroecological transition strategies and offers opportunities for learning from positive deviant situations (Herington and van de Fliert, 2018; Modernel et al., 2018; Steinke et al., 2019). However, these evaluations often lack underpinning by quantitative data on the use of agrochemical inputs (Larsen et al., 2019; but see Maeso et al., 2007; Blum et al., 2006) and their relation to crop productivity. Therefore, there is a need for a quantitative diagnosis of input use in vegetable production systems and a systemic overview of the relationship between agrochemical inputs and crop performance.

This study aims to evaluate the efficiency of agrochemical inputs in enhancing vegetable yields, to understand differences in terms of farm context, and to identify opportunities for ecologisation and ecological intensification in a context-specific manner. First, we assess the relationships between pesticide and nutrient inputs and crop productivity in greenhouse long cycle tomato, greenhouse short cycle tomato, onion, sweet potato, and strawberry, which are major vegetable crops in the south of Uruguay. Second, we identify groups of fields and farms with contrasting performances based on a conceptual model of ecological intensification (Tittonell et al., 2016) and considering the relationship between yield and pesticide and nutrient inputs. Third, we explore the association between farm input use and yield performance and farm resource endowment. Finally, we discuss the implications of our findings for environmental and health risks and ways to identify production systems that support an agroecological transition in a context-specific manner.

2. Materials and methods

2.1. Site description

The study was conducted in the south of Uruguay, where most of the vegetable production is concentrated. The area encompasses the departments of Canelones, San José, and Montevideo (34°21′S to 34°57′S – 55°40′W to 56°40′W) and covers approximately 4800 km^2. The climate in the region is humid subtropical. The average mean temperature is 17 °C (minimum: 11 °C, maximum: 23 °C), with light frosts between the end of May and September. Mean annual precipitation is 1200 mm, evenly distributed throughout the year, but with significant variation between years (Castaño et al., 2011). Main soil types in the region are classified as Mollic Vertisols (Hypereutric), Luvic/Vertic Phaeozems (Pachic), and Luvic Phaeozems (Abruptic/Oxyaquic) (Alliaume et al., 2013).

There are around 2000 vegetable farmers in the study area producing 7300 ha of field-grown crops and 350 ha of greenhouse crops (DIEA-MGAP, 2017). Typical greenhouses are "open greenhouses" made with nylon and wooden posts, ranging between 380 and 1000 m^2. Tomato is the main greenhouse crop produced in short (200 days or less) or long (more than 200 days) cycles. The most common short cycle tomato crops are grown in spring-summer (transplanted in August–September and harvested until January) or in summer-autumn (transplanted in January–February and harvest until June–July). Most common long cycle crops are transplanted between August and October and harvested until April–June (Berrueta et al., 2019). Onion is the main open field crop. The most common varieties are sown in April and May, transplanted from July till September, and harvested in December and January (Gimenez et al., 2013). Sweet potato is a summer open field crop, typically transplanted from October till December and harvested between March and April (Gimenez et al., 2013). Strawberry is mainly planted in open fields at the end of February and March, with imported cold-stored plants. The harvest period depends on the variety and management, but for most crops, production peaks from September to December (Scarlato et al., 2017).

2.2. Analytical framework

In our analysis, we focused on two categories of agrochemical inputs: nutrients and pesticides. From a production ecology perspective, nutrient inputs are growth limiting factors as they contribute directly to crop growth and their input levels determine the attainable yield level (van Ittersum and

Rabbinge, 1997; Zhengfei et al., 2006). On the other hand, pests and diseases pressure are growth reducing factors, which define the actual yield level (van Ittersum and Rabbinge, 1997). Pesticides can be considered as facilitating inputs as these indirectly affect yield by controlling or altering growth conditions (Zhengfei et al., 2006). Yet, pesticides are not directly involved in the basic biological processes of crop growth, such as nutrients are. We analysed the relationship between nutrients and pesticides inputs on yield separately and combined.

For our analysis, we adapted the concept of ecological intensification proposed by Tittonell et al. (2016) to represent the relationship between yield and pesticide and nutrient inputs in four quadrants (Fig. 1). The most favourable combination is high yields with low input levels. Intermediate combinations are high yields with high input levels, and low yields with low input levels, and the least desirable combination is low yields and high input use. This representation allows visualising pathways of change: “Ecologisation” as the process of maintaining yields while reducing input use, “Intensification” as the process of increasing yields with the same or lower input levels, or a combination of “Ecologisation” and “Intensification” (Fig. 1).

2.3. Data collection

We assembled a dataset on crop management and performance of long cycle tomato, short cycle tomato, onion, sweet potato, and strawberry crops by combining data from previous studies. The dataset contained data on 82 farms and 428 fields over the period 2012 to 2017 (Table 1). The farm sample was based on a typology of vegetable farms using the database of the Vegetable Growers Survey of the Ministry of Agriculture for South Uruguay and captured 5% of the farms producing onion and sweet potato and 10% of the farms producing strawberry and greenhouse tomato. For each crop, groups of farms were identified based on cluster analysis of crop yield, crop area and total crop production per farm. A representative sample of farms per crop was obtained by selecting farms proportional to the number of farms in each group and considering their geographic distribution with the assistance of the technical advisers of the region (Dogliotti et al., 2021; Scarlato et al., 2017). Self-subsistence farms and farms with more than 50% of off-farm income were excluded, resulting in a dataset of only commercial farms. According to Dogliotti et al. (2019) classification, the sample included 13% small family farms, 50% medium family farms, 20% specialised greenhouse farms, and 18% large family farms and medium entrepreneurs. For each crop, one to four fields were monitored per farm throughout two growing seasons.

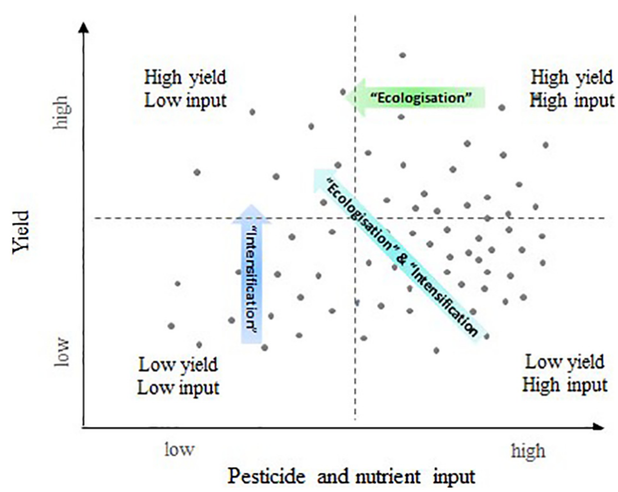

Fig. 1. Conceptual representation of pathways towards more sustainable commercial vegetable production systems in Uruguay. The four quadrants reflect combinations of yield and levels of pesticide and nutrient inputs (Tittonell et al., 2016). The two quadrants with high inputs represent an inefficient and polluting production situation. In contrast, the quadrant of low yields and low input levels constitute a situation where efficiency gains are possible. Different pathways of change can be identified: “Ecologisation” entails maintaining crop productivity while reducing inputs, and “Intensification” increasing productivity at sustainable input levels.

The dataset contained information on crop yield, pests and diseases pressure, and crop management. Management variables were selected using a functional analysis based on production ecology theory (van Ittersum and Rabbinge, 1997), where growth factors affecting yield are classified as growth defining, growth limiting, or growth reducing. The associated management variables collated in the database were plant density, crop cycle length, and planting date (growth defining factors), soil organic matter, soil nutrient, nutrient inputs and water availability (growth limiting factors), and pest and disease incidence, pesticide inputs, frequency of the same crop in the preceding three to five years (growth reducing factors). The dataset also contained information on farm resource endowment (farm size, vegetable crop area, labour type and availability, mechanisation level, and diversification of farm activities; Appendix A).

2.4. Data analysis

We conducted the analysis in five steps. First, we quantified the use of pesticides and nutrients and explored the associations between these inputs in each of the five crops using the complete dataset of 428 fields. Pesticide load in kg active ingredient (AI) per ha was derived by summing the AI applied at each application. Nutrient input was calculated as the cumulative amount of N, P, and K in organic and synthetic fertiliser inputs. We explored the relationships between pesticide load and the number of pesticide applications and between N, P, and K inputs by Pearson correlation coefficients for each crop. Associations between herbicide, insecticide, fungicide, and total pesticide load, number of pesticide applications, N, P, and K amounts were analysed by principal component analysis (PCA).

Second, we explored the relationship between yield and inputs of pesticides and nutrients, in conjunction with year, crop cycle length, planting date, plant density, soil organic carbon, pest and disease incidences (explanatory variables) in the five crops. We used Pearson correlation coefficients and mixed linear models to explore the associations. For each crop, mixed models included yield as response variable, and year, input use, and crop management variables as fixed effects, and farm was included as a random effect. Multicollinearity was assessed through the Variance Inflation Factor (VIF), and variables with VIF higher than five were excluded from the analysis. Residual plots confirmed that the models met homogeneity of variance criteria (Zuur and Ieno, 2016; Zuur et al., 2010). We used the complete dataset of each crop except for onion where we excluded three fields due to incomplete data, resulting in 122 fields.

Third, to explore the underlying drivers of the observed pesticide and nutrient input levels, we tested several hypotheses. For pesticide inputs, we considered variables related to pest and disease incidence and severity, crop and soil management, and environmental conditions that determine pest and disease occurrence. We analysed the relationships between pesticide inputs, other crop management, year, and pest or diseases incidence using PCA and linear mixed models for the crops where a significant relationship between yield and pesticide input was found. Linear mixed models included pesticide load as response variable, and year, pest or diseases incidence, and crop management variables as fixed effects (variables detailed in Appendix C, Table C1), and farm as a random effect.

For nutrient inputs, we considered soil nutrient status before crop establishment and crop nutrient balance. The relationship between N, P, and K inputs and soil organic carbon, soil P content, and soil K content was explored by Pearson correlation coefficients and PCA. Nitrogen, phosphorus, and potassium balances for each crop were estimated as:

$$\mathrm{Bal_X} = \mathrm{Input_X} - \mathrm{Yobs} * \mathrm{C_X} \tag{1}$$

where $\mathrm{Bal_X}$ is the balance for nutrient X (kg ha^{-1}). X refers to N, P, or K. $\mathrm{Input_X}$ is the supply of nutrient X (kg ha^{-1}). Yobs is the observed crop yield (Mg ha^{-1}), and $\mathrm{C_X}$ is the concentration of nutrient X in the harvested

Table 1
Overview of the crops, number of fields and farms, and assessment period in the dataset.

Crop	Number of fields	Number of farms[a]	Years evaluated	Reference
Onion	125	31 + 1 ES	2014/2015, 2015/2016	Dogliotti et al., 2021
Strawberry	76	13 + 1 ES	2012, 2013	Scarlato et al., 2017
Sweet potato	118	31	2015/2016, 2016/2017	Dogliotti et al., 2021
Short cycle tomato	70	20	2014/2015, 2015/2016	Berrueta et al., 2019
Long cycle tomato	39	18	2014/2015, 2015/2016	Berrueta et al., 2019

[a] ES: experimental station.

product (kg nutrient X Mg^{-1} product). C_X was based on Ciampitti and García (2012). For onion, strawberry, and sweet potato, we considered the nutrient concentration in the harvested product, assuming that crop residues are left in the field, which corresponds with standard farmer practices. For short and long-cycle tomato, we considered nutrient content in the entire crop because farmers remove all crop residues from the greenhouses at the end of the harvest period.

As most nutrients are applied before planting the crops, farmers base their fertiliser application rates on the expected attainable yields. We therefore also calculated nutrient balances for the attainable yield (Yatt) estimated as the 90th percentile highest yield per crop, using Eq. (1) and replacing Yobs by Yatt. The attainable yields were 41.1 Mg ha^{-1} for onion, 35.2 Mg ha^{-1} for strawberry, 44.9 Mg ha^{-1} for sweet potato, 23 kg m^{-2} for long cycle tomato, and 15 kg m^{-2} for short cycle tomato.

Fourth, we positioned the data in the four quadrants of the conceptual model in Fig. 1. Pesticide and nutrient inputs were converted to indices ranging from 0 to 50, where 0 equalled 0 kg input, and 50 was equivalent to the maximum amounts of pesticides or nutrients applied. The sum of both indices resulted in the input index, which ranged from 0 to 100. The boundary between the high and low yield and input quadrants was taken to be the average of yield and input index across all fields, respectively.

Fifth, we explored the effect of farm resource endowment on the relationship between yield and input index. We used the farm-level dataset, excluding data from experimental stations (one onion and one strawberry case). We projected the data in the four quadrants diagram of Fig. 1 based on yield and input index averaged across the farm's fields for each crop. Each of the four groups were characterised in terms of farm size (ha), area of vegetable crops (ha), area of the crop of interest (ha), greenhouse area (ha), total labour (full-time equivalent), ratio family labour/total labour, ratio permanent labour/total labour, mechanisation level, and diversity of activities. Characteristics of the farm groups were compared using Kruskal-Wallis tests.

Data analyses were performed using R 3.6.3 (2020-02-29) using the following R-packages: “ggplot2” (Wickham, 2016), “factoextra” (Kassambara and Mundt, 2020), “gridExtra” (Auguie, 2017), “PerformanceAnalytics” (Peterson and Carl, 2020), “corrplot” (Wei and Simko, 2017), “tydiverse” (Wickham et al., 2019), “lme4” (Bates et al., 2015), “ggpubr” (Kassambara, 2020a), and “rstatix” (Kassambara, 2020b).

3. Results

3.1. Assessment of pesticide and nutrient inputs

Pesticide input was greatest in strawberry and long cycle tomato, both in terms of the number of applications (20 and 18, respectively) and pesticide load (21 kg AI ha^{-1} in both crops; Table 2). Short cycle tomato and onion revealed intermediate pesticide input levels, and sweet potato had the lowest pesticide input (Table 2). In strawberry and onion, fungicides were the most prevalent pesticides, while in short and long cycle tomato, both insecticides and fungicides were common (Table 2). Nutrient inputs were greatest for long cycle tomato (N, P, and K totalling 1127 kg ha^{-1}), followed by short cycle tomato, strawberry, onion, and sweet potato (Table 2). The data showed clear crop-specific patterns in pesticide and nutrient input levels (Fig. 2), despite considerable variation across fields within the same crop.

There was a positive correlation between the number of pesticide applications and pesticide load per ha in all crops (Pearson's r ranging between 0.3 and 1.0, $p < 0.05$). There were significant positive correlations between the number of applications and pesticide load per ha of the main type of pesticide (insecticides, fungicides, and herbicides) used per field (r range 0.3–0.9, $p < 0.05$; Appendix B). In addition, there were positive correlations between N, P, and K inputs per field (r range 0.3–0.8, $p < 0.001$). These significant positive correlations indicate that farmers who used a higher amount of a particular pesticide or nutrient type also tended to use higher amounts of other types of pesticides or nutrients.

3.2. Relationship between yield and pesticide and nutrient inputs

The relationships between yield and pesticide and nutrient inputs were crop-specific and often weak (Table 3, Appendix C). Yields of sweet potato and short cycle tomato were not significantly associated with pesticide input, and strawberry yield was negatively related to fungicide use. There was a marginally significant positive association between insecticide applications and the yield of long cycle tomato, which was also significantly associated with pesticide load ($r = 0.34$, $p = 0.03$). Onion yield was positively associated with fungicide use ($r = 0.40$; $p < 0.01$; Table 3). However, pest incidence in long cycle tomato was not significantly associated

Table 2
Yield, amounts of N, P, and K applied per ha, amounts of active ingredient (AI) per ha, and number of pesticide applications per ha for the five focal crops.

Crop	Yield	N	P	K	Total	Fungicides	Insecticides	Herbicides	Total
	Mg ha^{-1}	kg ha^{-1}				(kg AI ha^{-1})			
Onion	26.5 ± 10.3	128 ± 78	52 ± 25	41 ± 67	222 ± 127	10.7 ± 8.0	0.5 ± 0.6	1.2 ± 0.9	12 ± 9
Strawberry	21.5 ± 10.7	123 ± 77	85 ± 53	168 ± 414	376 ± 242	18.9 ± 19.9	0.9 ± 1.1	1.7 ± 0.9	21 ± 21
Sweet potato	29.6 ± 11.0	39 ± 28	26 ± 24	16 ± 22	81 ± 50	0	0.2 ± 0.4	0.5 ± 0.4	0.7 ± 0.6
Long cycle tomato	157.0 ± 54.7	341 ± 228	146 ± 140	640 ± 349	1127 ± 536	12.2 ± 12.5	8.5 ± 6.9	0.02 ± 0.10	21 ± 17
Short cycle tomato	82.9 ± 37.3	222 ± 164	83 ± 77	354 ± 222	659 ± 344	7.7 ± 8.9	3.3 ± 3.0	0.01 ± 0.09	11 ± 10

Crop	Fungicides	Insecticides	Herbicides	Total
	Number of applications			
Onion	6.9 ± 4.1	1.5 ± 1.7	2.8 ± 1.6	10 ± 5
Strawberry	14.6 ± 14.2	5.1 ± 5.5	4.5 ± 2.6	20 ± 16
Sweet potato	0	0.5 ± 0.9	1.3 ± 1.1	1.8 ± 1.5
Long cycle tomato	11.7 ± 6.9	15.1 ± 5.5	0.03 ± 0.16	18 ± 6
Short cycle tomato	7.0 ± 4.6	9.0 ± 3.9	0.04 ± 0.27	11 ± 4

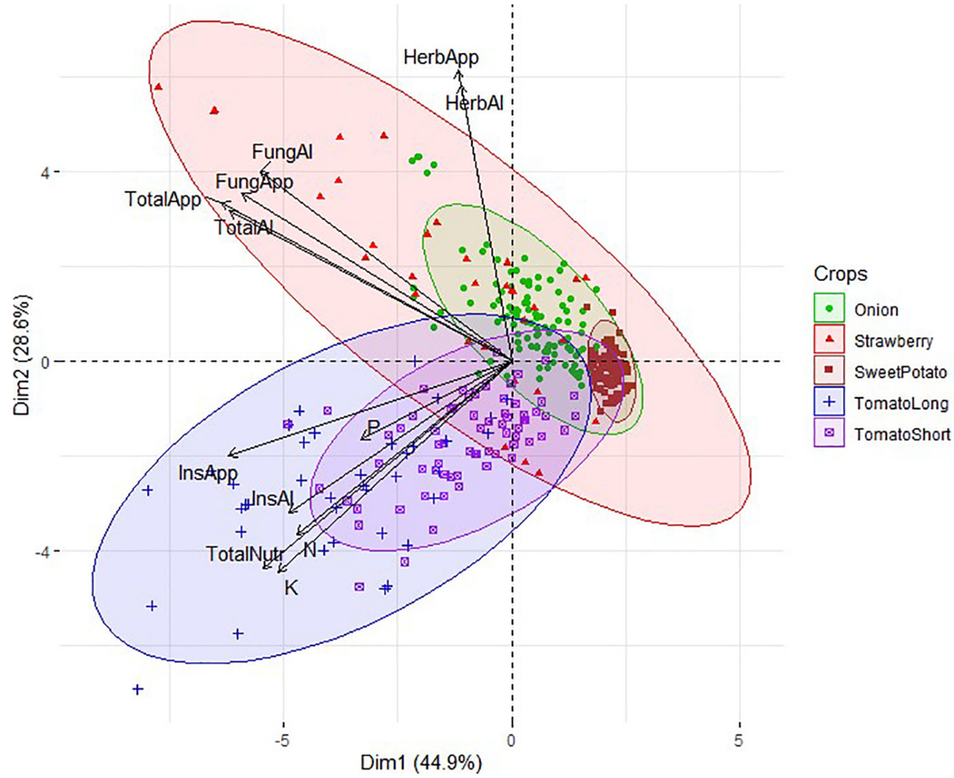

Fig. 2. Principal component analysis considering herbicides (Herb), fungicides (Fung), insecticides (Ins) and total (Total) number of pesticides applications (App) and AI load per ha (AI), N, P, K and total (TotalNutr) nutrient input per ha. Crops are indicated with specific markers. $N = 428$ fields. The total variation explained by the first two principal components is 74%.

Table 3
Yield determinants of the five crops based on linear mixed models with the variable Farm as random effect.

Variable	Units	Onion	Strawberry	Sweet potato	Long cycle tomato	Short cycle tomato
FungAI	kgAI ha^{-1}	**439 (105)***	**−217 (101)***	NA	19 (665)	−61 (461)
InsAI	kgAI ha^{-1}	185 (1337)	−818 (1766)	−930 (2210)	−554 (1190)	1248 (1648)
HerbAI	kgAI ha^{-1}	−126 (924)	NA	3470 (2167)	NA	NA
InsApp	Number of applications	High VIF	High VIF	High VIF	2659 (1539)•	1692 (1325)
N	kg ha^{-1}	**−28 (12)***	30 (21)	−79 (42)	**108 (41)***	−45 (30)
P	kg ha^{-1}	42 (13)	High VIF	24 (53)	−46 (82)	55 (53)
K	kg ha^{-1}	30 (17)•	High VIF	−6 (48)	−5 (32)	27 (21)
Year	2 years per crop	2644 (1452)	−1444 (2576)	**9795 (2328)***	−17,410 (15180)	**−19,872 (9664)***
Season cycle	Spring/Autumn	NA	NA	NA	NA	**58,268 (9141)***
Plant density	Number of plants m^2	**924 (179)***	2895 (1930)	**4368 (1278)***	−8673 (19680)	4926 (8682)
Crop length	Number of days	**147 (48)**	NA	**218 (76)**	**818 (250)**	**817 (198)***
Planting date	Number of days (strawberry 1 = 27/2, sweet potato 1 = 1/10)	NA	**−99 (45)***	−13 (58)	NA	NA
Completing date	Number of days (1 = 26/3)	NA	−58 (37)	NA	NA	NA
Soil organic carbon	%SOC	**6052 (1980)**	−2077 (3087)	1173 (26001)	**35,070 (14340)***	2909 (6908)
N during crop cycle	kg ha^{-1}	NA	**375 (110)**	NA	NA	NA
Whitefly	Scale 0–3	NA	NA	NA	−10,690 (8455)	−3133 (4264)
Tomato leaf miner	Scale 0–2	NA	NA	NA	−5768 (9531)	−8661 (4995)
Tomato frequency	From 0 to 2	NA	NA	NA	**−29,040 (12510)***	−2467 (6899)
Tomato sequence	From 0 to 3	NA	NA	NA	21,470 (13610)	2680 (5625)
Mildew incidence	From 0 to 4	−4315 (3857)	NA	NA	NA	NA
Mildew severity	From 0 to 1	−2019 (1809)	NA	NA	NA	NA
Water during cycle	mm	NA	NA	1 (12)	NA	NA
Number of fields		122	76	118	39	70
Number of farms		32	14	31	18	20

FungAI, InsAI, HerbAI: Active ingredient (AI) load per ha for fungicides (Fung), insecticides (Ins), and herbicides (Herb). InsApp: number of insecticides applications. N, P, K: nutrient input in kg ha^{-1}. Whitefly, tomato leaf miner, tomato frequency and sequency, and mildew incidence and severity scales detailed in Appendix A, table A1. High VIF: variables excluded from the model due to high collinearity. NA is not applicable for the crop. Estimates are shown, with standard error between brackets and statistical significance in bold and with asterisks *.

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.
• $p < 0.1$.

with insecticide use in both years, and downy mildew incidence and severity in onion were not significantly associated with fungicide use. Pesticide input was positively related to crop cycle length (tomato long cycle, $p < 0.05$; onion, $p < 0.01$) (Appendix C).

Yields of strawberry, short cycle tomato, and sweet potato were not associated with N, P, or K inputs. In contrast, long cycle tomato yield was positively related to N, and onion yield was weakly and positively associated with K inputs, but negatively associated with N inputs (Table 3, Appendix D). There were positive correlations between N input and SOC ($r = 0.20$, $p < 0.001$), P input and soil P content ($r = 0.26$, $p < 0.001$), and K input and soil K content ($r = 0.63$, $p < 0.001$), indicating that decisions on nutrient input levels were not based on soil nutrient status (Appendix D). Moreover, most fields had nutrient imbalances, irrespective of whether nutrient uptake was estimated from observed yields or from attainable yields (Appendix D), indicating that fertilisation was not tailored to crop nutrient demands. P balances were generally positive for all crops, while K balances were generally negative, except for strawberry, where most fields had a positive K balance. N balances were generally positive in strawberry and onion, and negative in tomato and sweet potato fields.

3.3. Variability in yields and associated inputs

There was a high variation in pesticide and nutrient input levels in onion, strawberry, long and short cycle tomato (Fig. 3). High yields and low input index was achieved in 16% of the onion fields, 24% of the strawberry fields, 29% of the short cycle tomato greenhouses, and 18% of the long cycle tomato fields. In long cycle tomato, we found three cases with low yields and high input index (Fig. 4). Overall, there were few cases with an input index higher than 60, indicating that fields with relatively high pesticide and nutrient inputs were rare.

3.4. Farm-level performance

For all crops, variability in yield exceeded variability in input index at the farm level (mean coefficients of variation 27% and 20%, respectively), indicating that input management was relatively constant across fields and years at most farms. High yields and low input index values at the farm level were achieved on 10% of the farms for onion, 15% for strawberry, 30% for short cycle tomato, and 17% for long cycle tomato (Fig. 5). The main type of input differed among farms, with some mainly using pesticides while others mainly used nutrients.

There was a statistically significant difference in yield and input index between the farms in the four quadrants for all crops (Kruskal-Wallis test $p < 0.05$). Farms in the four quadrants did not differ significantly in size, vegetable crop area, area of the crop of interest, total labour, mechanisation level, and diversification in farm activities (Kruskal-Wallis test $p > 0.05$), except for of onion, where farms of the low yield - low input index quadrant had a higher ratio of family to total labour than farms in the high yield - high input index quadrant ($p < 0.05$) (Appendix E).

4. Discussion

In this study, we assessed the relationships between pesticide and nutrient inputs and yield in onion, sweet potato, short cycle tomato, long cycle tomato, and strawberry during two years per crop on 5–10% of the farms in the south of Uruguay. We reported four key findings. First, relationships between pesticide and nutrient inputs and yield were generally weak or non-significant, indicating inefficiencies and overuse of inputs. In many cases, we could not find agronomic explanations for the level of pesticide and nutrient use. Second, while we generally report high agrochemical input levels in Uruguayan vegetable production systems, we also showed substantial variation in input use among crops, fields (including tomato greenhouses), and farms. Third, combinations of high yields and low

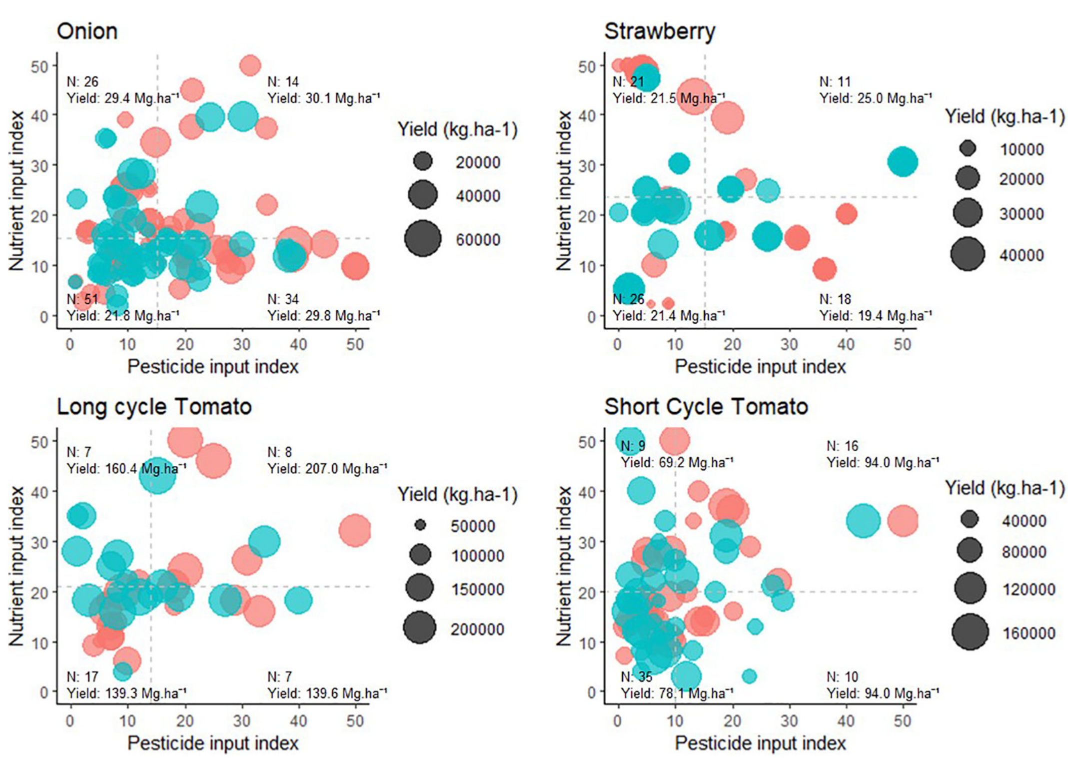

Fig. 3. Relationships between yields and pesticides and nutrients input index for onion, strawberry, and long and short cycle tomato. Each bubble corresponds to one field. Bubble size corresponds with yield. Colours indicate years: red corresponds to the first year, and green corresponds to the second year. Each panel is divided into four quadrants based on average values per axis. In each quadrant the number of fields (N) and the average yield are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

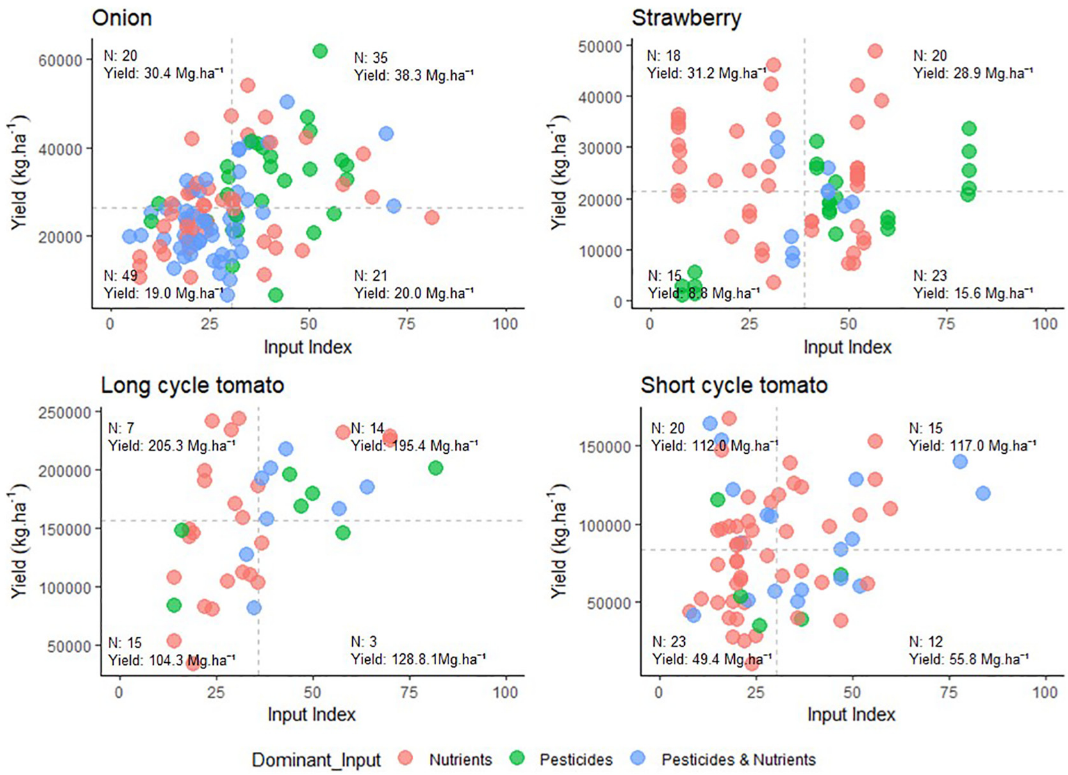

Fig. 4. Relationships between yield and input index for onion, strawberry, long cycle tomato, and short cycle tomato. Input index represents the sum of pesticide and nutrient input index values. Each panel is divided into four quadrants based on average values per axis. In each quadrant, the number of fields (N) and the average yield are shown. The colour of markers indicates the dominant input: red ($\geq$60% nutrient input), green ($\geq$60% pesticide input), or blue (both pesticides and nutrients between 41 and 59%). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

input levels were found on 21% of the fields and on 17% of the farms for onion, strawberry, and tomato, indicating better than average management practices. Finally, relationships between yield and input use at farm level were not related to farm resource endowment, except for onion where farms with a low yield - low input index quadrant had a relatively high family to total labour ratio.

We found that in many cases yield levels were not related to input levels. For instance, pesticide use was not related to short cycle tomato yield or sweet potato yield and negatively related to strawberry yield. Although fungicides were strongly associated with onion yields and insecticides were weakly associated with long cycle tomato yields, there was no relation between disease or pest incidence and pesticide use. We found a positive association between yield and crop length and between crop length and pesticides use in onion and long cycle tomato. These findings are in line with results of yield gap analyses of Scarlato et al. (2017), Berrueta et al. (2019), and Dogliotti et al. (2021), who found that yield gaps were mainly explained by other factors than pesticides. Our findings align with findings from previous studies from France (Lechenet et al., 2014) and worldwide (Popp et al., 2013), questioning the need to use large amounts of synthetic pesticides to achieve high yield. Apart from agronomic reasons, there are also compelling reasons to reduce pesticide inputs from an environmental and worker health and safety perspective (Jepson et al., 2014, 2020; Pimentel, 2005) as an average pesticide input of 21 kg AI ha^{-1} in long cycle tomato and strawberry are likely to lead to substantial impacts.

Nutrient inputs only explained yields in long cycle tomato and onion, and, consistently across all crops, nutrient inputs were not related to crop requirements or soil nutrient status. We detected nutrient imbalances for all crops. Nutrient input levels were positively related to soil nutrient contents before establishing the crop, suggesting that farmers do not base their fertilisation decision making on soil nutrient status. On the contrary, our data suggest that the imbalanced soil nutrient status might be the result of a standard fertilisation routine that is repeated each year. Strong imbalances in nutrient inputs and crop demand and their impact on nutrient accumulation, leaching, or depletion of soil stocks have been reported as a global phenomenon and as particularly intense in developing countries (Bennett et al., 2001; Tan et al., 2005). Indeed, in Uruguay high N and P accumulation in surface water in vegetable production areas have been reported (Barreto et al., 2017). Our findings also point towards major risks of N leaching, P accumulation, and K depletion in vegetable systems in south Uruguay, and stress the need for better informed fertilisation decision making.

While our study quantified for the first time the high agrochemical input levels in Uruguayan vegetable production systems, we also showed substantial variation in management among crops, fields, and farms. The same yield level was achieved with a wide range of input levels in all crops. Our results align with findings of Lechenet et al. (2016), who found no relation between pesticides use and productivity on vegetable crops in France, Abunyuwah et al. (2020), who found pesticide overuse and high variability among tomato crops in Ghana, and Ahovi et al. (2021) who found overuse and high inefficiencies of pesticides and fertilisers in Dutch greenhouse vegetable production, but also high variability among farms. Although most of the farms in our sample were conventional, some conventional farms had low input levels, which were comparable to organic farms. Similar to what Marliac et al. (2016) and Pépin et al. (2021) found for organic vegetable farms in France, our results show that “conventional farming” may entail a wide variation in practices and performances.

For onion, strawberry, and the two tomato crops, 21% of the fields and 17% of the farms were identified as “positive deviants” (Herington and van de Fliert, 2018), which combined high yields and low pesticide and nutrient inputs. These positive deviants show that there is space to reduce input use while maintaining or increasing yields. The identification, understanding, and sharing of these successful examples may provide insights

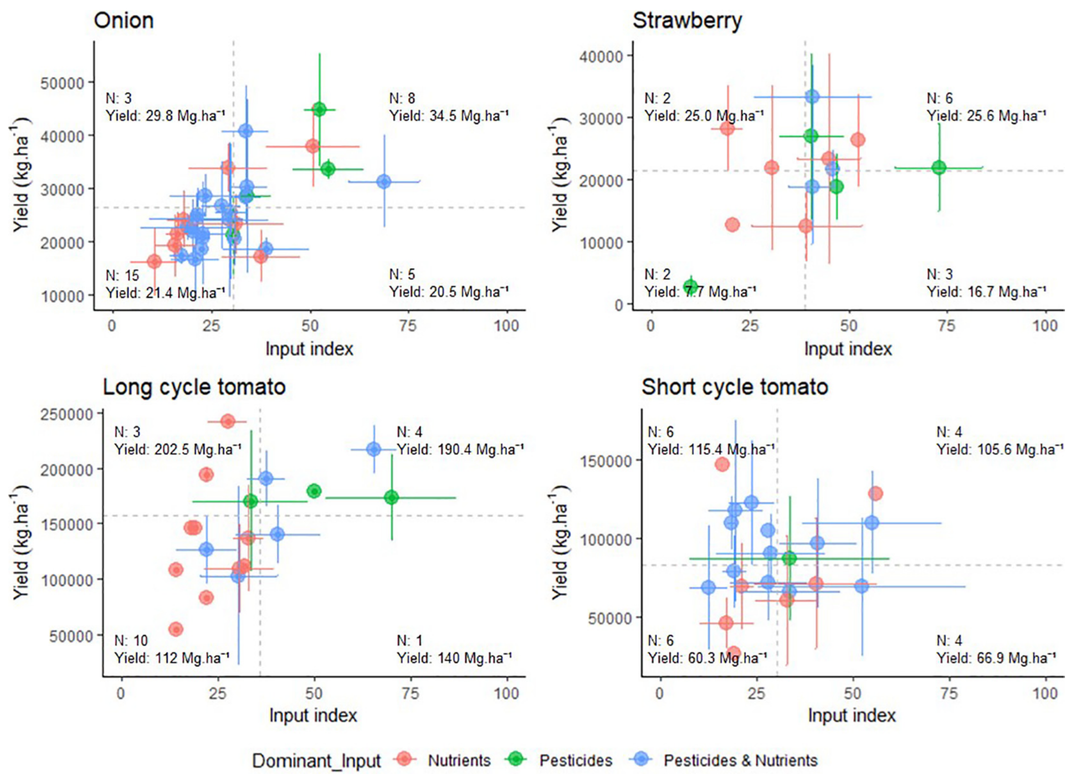

Fig. 5. Relationships between yield and input index at the farm level for onion, strawberry, short cycle tomato, and long cycle tomato. Each panel is divided into four quadrants based on average values per axis. In each quadrant, the number of farms (N) and the average yield is shown. Markers indicate the average yield and average input index of each farm, and bars are standard deviations of yield and input index for each farm. The colour of markers indicates the dominant input: red (≥60% nutrient input), green (≥60% pesticide input), and blue (both pesticides and nutrients between 41 and 59%). Number of farms: 31 for onion, 13 for strawberry, 18 for long cycle tomato, and 20 for short cycle tomato. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

into how to transition to more sustainable production systems and may help promote changes in other farmers' attitudes and practices (Bakker et al., 2021; Modernel et al., 2018). A more detailed analysis of farmers' decision-making on input use and the factors driving this process (Bakker et al., 2021; Daxini et al., 2019; Doran et al., 2020) could shed further light on effective incentives to support policies for the transition towards more sustainable farming practices. In addition, along with other studies (Ahovi et al., 2021; Lechenet et al., 2016), our findings also point towards the difficulty for farmers to reduce their agrochemical input use within the current agricultural innovation system which revolves around agrochemical marketing and sales (Jallow et al., 2017; Jin et al., 2015; Schreinemachers et al., 2017). Therefore, besides research, targeted governmental policies are needed to regulate agrochemical input use and promote the transition to a more sustainable food system (Tittonell, 2014).

Yield–input relations were not clearly related to farm resource endowment with except for onion where smallholders tended to have low input levels and low yields. This implies that farm resource endowment would not be limiting the scope to improve yields while decreasing inputs use. We found similarities between the use of inputs and their relation to yields for different fields of a farm, and we consistently found that higher inputs of one type of pesticide coincided with higher inputs of other types of pesticides across years and crops and without apparent relation to agronomic factors. We also found imbalances between the required and supplied amounts of crop nutrients. These findings support the idea that current pesticide and nutrient management is not so much driven by agronomic criteria or best management practices, but relies on personal experience, tradition, or intuition (Nuthall and Old, 2018), i.e., a consistent "*way of doing*" or "*routine of doing*" of each farmer that is congruent across fields and years, which therefore manifests itself at the farm level. Although our study focused on input use at the field level, our findings indicate that farmers use a standard field-level management approach across the whole farm and years, irrespective of variation in soil and weather conditions. This emphasises the need to consider changes from a systemic, whole-farm perspective.

To assess possible transition routes to strengthen agronomic and environmental performance (Figs. 4, 5), we positioned commercial vegetable systems in Uruguay in a productivity-input use plane based on Tittonell et al. (2016). The 90% quartile yields in the commercial fields were consistently higher or equal to yields attained under experimental conditions for all five crops (Berrueta et al., 2019; Gimenez et al., 2013; Scarlato et al., 2017). However, yields gaps were on average around 50% (Berrueta et al., 2019; Dogliotti et al., 2021; Scarlato et al., 2017). The difference in input index between the high yield - high input index and high yield - low input index farm groups for all crops was 50% (Table E1), indicating that in many situations high yield could be achieved with half of the input used. Moreover, for tomato and strawberry crops, the timing of nutrient applications did not match crop requirements in most cases, leading to nutrient losses and inefficiency (Berrueta et al., 2019; Scarlato et al., 2017). Therefore, by using best management practices yields can be increased with less pesticide and fertiliser inputs. Previous studies showed that the main changes required to reduce yield gaps are not input-related, but revolve around choice of planting dates and planting density, soil organic matter content, and frequency of the crop in the rotation (Berrueta et al., 2019; Dogliotti et al., 2021; Scarlato et al., 2017). In some cases more efficient use of inputs was required, e.g. through timing of nutrient applications and avoiding calendar pesticide applications. Such strategies would contribute to both ecological intensification and ecologisation processes. Moreover, there are alternative practices to reduce pest damage without using pesticides contributing to an ecologisation process, such as soil solarisation in greenhouses and crop rotation in field crops, or the use of alternative inputs, like entomopathogenic fungus and predators for biological control that could substitute chemical pesticides (Basso et al., 2020).

We found considerable variation in the amount and type of inputs used among farms. Some farmers tended to overuse only pesticides, others overused only nutrients, yet others overused both input types. Furthermore, and in line with findings of Larsen et al. (2019), the main type of pesticide or nutrient used differed among farms according to their crops. Consequently, the changes needed to reduce the reliance on agrochemicals are largely farm specific. This calls for a detailed diagnosis and systemic redesign that considers the specific situation of each farm and the synergies and trade-offs between the crop and farm level, as has been done in co-innovation projects in the Rio de la Plata region (Colnago et al., 2021; Dogliotti et al., 2014; Rossing et al., 2021). Berrueta et al. (2021) showed that recommendations from crop research need to be tailored to farm context and objectives, and consider synergies and trade-offs to have greater economic and environmental impacts. The beginning of such a systemic diagnosis and redesign could focus on what has been defined as levels one and two of the agroecological transition (Gliessman, 2015; Nicholls et al., 2016), which implies increasing efficiencies and changes in the type of inputs used, and paves the way for redesign as the third level of the agroecological transition.

Various studies have recently addressed how a transition to more sustainable systems may be fostered (Berrueta et al., 2021; Lacombe et al., 2018; Markard et al., 2012; Melchior and Newig, 2021; Ollivier et al., 2018). Starting an agroecological transition from a systemic diagnosis and redesign requires investment in high-quality long-term and systemically oriented extension services capable of contributing to this process. It also requires the development of local context-specific knowledge and technologies to deepen the ecologisation process. Such knowledge and technologies should be developed in a participatory way and with a holistic and systemic perspective, focused on promoting and enhancing ecological processes to support production. For example, an Agroecological Crop Protection (ACP) approach may be more promising than an Integrated Pest Management (IPM) approach because IPM often still revolves around the (reduced) use of pesticides (Deguine et al., 2021). ACP aims to promote the ecological health of agroecosystems by directly or indirectly optimising interactions between living communities (plant, animal, microbial) below and aboveground, based on two pillars, biodiversity and soil health (Deguine et al., 2021). These principles are well known in agroecology (Nicholls and Altieri, 2007), but we lack context-specific actionable knowledge to help farmers apply them. For example, how to improve crop nutrition based on soil organic matter management and organic amendment dynamics? Or, how to design and manage crop diversity and soil microbiome diversity to promote natural pest regulation? New knowledge on translating general principles into practices in a concrete situation would foster and support redesign processes for an agroecological transition.

5. Conclusion

This paper documents the high pesticide and fertiliser use in vegetable production systems in south Uruguay using two years of data on five vegetable crops and 428 fields. In most fields, input levels were not reflected in yield output, demonstrating a lack of agronomic justification for agrochemical input. Such overuse of inputs imposes serious environmental and human health risks and highlights the need to rethink current agronomical practices to arrive at context specific, judicious input use. Positive deviant farms, which combined high yields with low input levels, were found in all five crops in the study, refuting the often held belief that high agrochemical use is required to obtain high productivity and providing inspiring examples of alternative management. Transitioning to a more sustainable state calls for a detailed diagnosis and systemic redesign at the crop and farm level involving farmers to bring about changes in engrained practices, investment in high-quality systemically oriented extension services to support farmers in the changes, and the generation of local context-specific knowledge and technologies to enhance ecologisation.

CRediT authorship contribution statement

Conceptualization: MS, SD and WR; methodology: MS, SD, FB and WR; data handling and analysis: MS; writing, original draft: MS, manuscript review and editing: MS, SD, FB and WR.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.152248.

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