An analysis of yield gaps and their causes in greenhouse tomatoes in the South of Uruguay

Name student: Martha Lammers
Period: November 2014- December 2015

Farming Systems Ecology Group

Droevendaalsesteeg 1 – 6708 PB Wageningen - The Netherlands

An analysis of yield gaps and their causes in greenhouse tomatoes in the South of Uruguay

Name student: Martha Lammers
Registration number student: 911105498160
Credits: 36
Code number/name course: FSE-80436
Period: November 2014 – December 2015
Supervisors: Walter Rossing and Santiago Dogliotti
Professor/Examiner: Felix Bianchi

Outline

Preface

This research is done as part of my Master Plant Science at the University of Wageningen in the Netherlands. This thesis has contributed to project FPTA-288, conducted by the Faculty of Agronomy and funded by INIA with the title 'Análisis y jeraquización de factores determinantes de las brechas de rendimiento y calidad en los principales cultivos hortícolas del Uruguay' (in English: Analysis and ranking of factors determining yield-gaps and quality of the major horticultural crops in Uruguay), led by Santiago Dogliotti. It has the objective to increase the sustainability of horticultural family farms in Uruguay by reducing the yield-gaps, improving the resource use efficiency and reducing the environmental impact.

I would like to give acknowledgements to all the producers that participated in this study, without them doing this study would be impossible. Especially thanks to Cecilia Berrueta and Santiago Dogliotti who led the project and incorporated me into it. To Walter Rossing for his supervision and evaluation. To the agronomic engineers C. Berrueta, G. Patrón, A. Vieta, P. Gonzalez, L. Motta y V. Font for bringing us in contact with the producers of every region. To Mario Reineri for his collaboration in the soil lab. To Alejandra Borgers for her help with the statistics. To Facundo Reherman for his field assistance. To INIA, 'Instituto Nacional de Investigación Agropecuaria' of Uruguay for the financing and supply of materials for the project.

Martha Lammers, MSc.
November 2015

Abstract

Tomatoes for fresh consumption are economically the most important horticultural crop in Uruguay. The average yield of greenhouse tomatoes between 2002 and 2010 fluctuated around 9.3 kg m^{-2} in the South of Uruguay, with a high variation in yields between producers. The actual yield gap of greenhouse tomatoes in the South of Uruguay is estimated at 54%. Knowing which factors explain these yield-gaps is the first step to design strategies to reduce the yield-gaps between producers. The purpose of this thesis is to contribute to the reduction of the yield-gaps in greenhouse tomatoes in the South of Uruguay, by quantifying them and identifying their main causes. From July 2014 until May 2015, 22 crops were evaluated in a representative sample of 18 producers. The methodology used is based on the Regional Agronomic Diagnosis and Yield-gap analysis. Variables were analysed related to the potential yield, limited yield and reduced yield. Data was analysed using cluster analysis, path analysis, Spearman correlations and CART analysis. The average yield of the crops was 9.4 ± 4.6 kg m^{-2} in the year 2015, with big differences between yields, ranging from 0.0 to 20.1 kg m^{2}. The yield gap was approximately 48%. The yield component that explained more the differences in yield was the length of the growing cycle. The major cause of the variability in yield was the total amount of potassium added by fertigation throughout the growing cycle. Crops with high input of potassium (>20.9 g m^{-2}, N=10) had an average yield of 13.4 ± 3.0 kg.m^{-2}. Crops with low input of potassium (<20.9 g m^{-2}, N=11) had an average yield of only 6.6 ± 1.5 kg m^{-2}. Among the crops with low potassium input, two groups were found, distinguished by the number of hours a day the relative humidity was under 50%. Crops with less hours a day under 50% RH (<4,75 hours, N=5) had a yield of 8.0 ± 0.8 kg m^{-2}. The crops with more hours a day under 50% RH (>4.75 hours, N=6) had a yield of 5.4 ± o.6 kg m^{-2}. In order to contribute to the reduction of yield-gaps, adaptations in management could be made without the increase of production costs. This adaptations would include better crop planning and better fertilizer management regarding amounts and moments of application. A first step for better humidity control could be placing humidity and temperature sensors inside the greenhouses.

Keywords: Greenhouse tomato, yield-gap, regional agronomic diagnosis (RAD), Uruguay

1. Introduction

1.1 Yield-gaps

One of the biggest challenges in agronomy is the determination and ranking of the major causes of yield gaps. Yield-gaps can be considered as the difference between the potential yield and the actual yields of farmers in a certain place and time of interest (Fermont et al 2009, Van Ittersum et al. 2013, Lobell et al. 2009). The potential yield is the maximum possible yield that can be achieved in certain agro-ecological conditions and is defined by factors such as cultivar features, radiation, temperature and CO_2 (Van Ittersum and Rabbinge, 1997, Van Ittersum et al. 2013). Potential yield is a concept that can be quantified using crop growth models but in practice can be found only in very few cases, such as greenhouses in the Netherlands. Usually, however, maintaining potential growth conditions is technically and economically not feasible. Most farmers do not achieve the potential yield, but a much lower actual yield that is limited by water and nutrients, and reduced by weeds, pest, diseases and pollutants (Van Ittersum et al. 2013). In practice, not so much the theoretically potential yield, but yield levels derived from field experiments, or maximum yields achieved by farmers in a region may be used to define the yield gap (Lobell et al. 2009). The knowledge about the factors that contribute to yield-gaps in crops is essential for sustainable intensification of agriculture , which has the objective to increase both yield and environmental sustainability of crop production (Garnett et al. 2013). The challenge is to be able to identify which of the multiple factors influences the yield more, and to quantify the possible improvements. Lobell et al. (2009) made a list of biophysical and socioeconomic factors that commonly affect crop growth and yields in farmers' fields (Table 1).

Table 1. Common factors that contribute to yield losses in farmers' fields (Lobell et al. 2009).

Biophysical factors
Nutrient deficiencies and imbalances (nitrogen, phosphorus, potassium, zinc, and other essential nutrients)
Water stress
Flooding
Suboptimal planting (timing or density)
Soil problems (salinity, alkalinity, acidity, iron, aluminium, or boron toxicities, compaction, and others)
Weed pressures
Insect damage

Diseases (head, stem, foliar, root)
Lodging (from wind, rain, snow, or hail)
Inferior seed quality
Socioeconomic factors
Profit maximization
Risk aversion
Inability to secure credit
Limited time devoted to activities
Lack of knowledge on best practices

The challenge of determining limiting factors and quantifying improvements has been addressed already for a couple of decades under the name of regional agronomic diagnosis' (RAD) or yield-gap analysis (Doré et al. 2008, Lobell et al. 2009). RAD is a methodological framework used in crop systems research to study the variations of yields at zone- or regional level by a crop systems approach, as well as a way to understand the relation between the production results and the farmers' practices. RAD bases its diagnosis on annual on-farm surveys, and environment and crop-yield build-up monitoring. The major goal of RAD is to identify and rank limiting factors for crop yield on the regional scale (Doré et al. 1997, Doré et al. 2008).

1.2 Problem description

Horticulture in Uruguay is oriented towards the internal market to supply fresh and minimally processed products. The vegetables are supplied by two main production zones, 'la Zona Sur' which is 80 km around Montevideo, and 'la Zona Litoral Norte' which is in the region of Salto. There are about 2600 farms in Uruguay that have horticulture as principal source of income (DIEA, 2013). Around 88% of the farms in Uruguay that have horticulture as main source of income are family farms where more than half of the workforce is provided by the family itself (Dogliotti et al, 2013). Typically, the greenhouses in Uruguayan farms are made of wood and plastic, a structure originating from Italy (Figure 1).

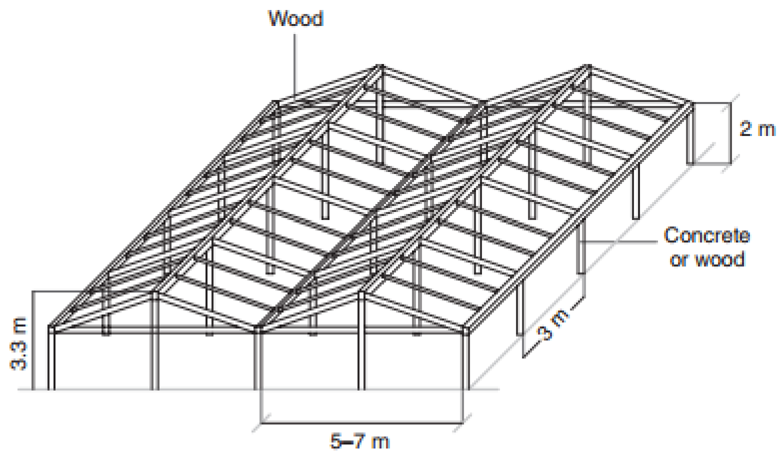


Figure 1. Greenhouse structure originated from Italy.

From 1992 to 2004, average prices for horticultural products dropped by 50% (Alliaume et al., 2013), while production costs (energy and agro-chemicals) increased which led to lower family incomes (Dogliotti et al., 2013). Influenced by this, family farms in the South of Uruguay responded by intensification and specialization in order to maintain their income (Dogliotti et al., 2013). Consequently, this has led to a reduced number of different crops per producer, and an increase in the use of irrigation and agrochemicals (Dogliotti et al., 2013). The intensification and specialisation of production systems without a proper planning caused an imbalance in the organisation of the horticultural farms, causing an inefficient use of production resources, higher dependency on external inputs and a higher environmental impact (Dogliotti et al., 2012). Furthermore, the pressure on soils, labour and capital has been increased (Dogliotti et al., 2012). The South of Uruguay has the highest degree of soil erosion, with 60-70% of the area moderately to severely eroded (Alliaume et al., 2013) (Figure 2). Due to increased tillage, reduced soil cover and organic matter supply and lack of erosion control measures, the soil has erosion rates higher than tolerable and the soil has a negative organic matter balance (Dogliotti et al., 2013). These factors aggravate the environmental problem that is already serious in the region and it has a negative impact on crop productivity and production costs (Alliaume et al., 2014). Overall, the sustainability of most family horticultural farms is in the long run threatened by insufficient income and the continuous deterioration of natural resources.

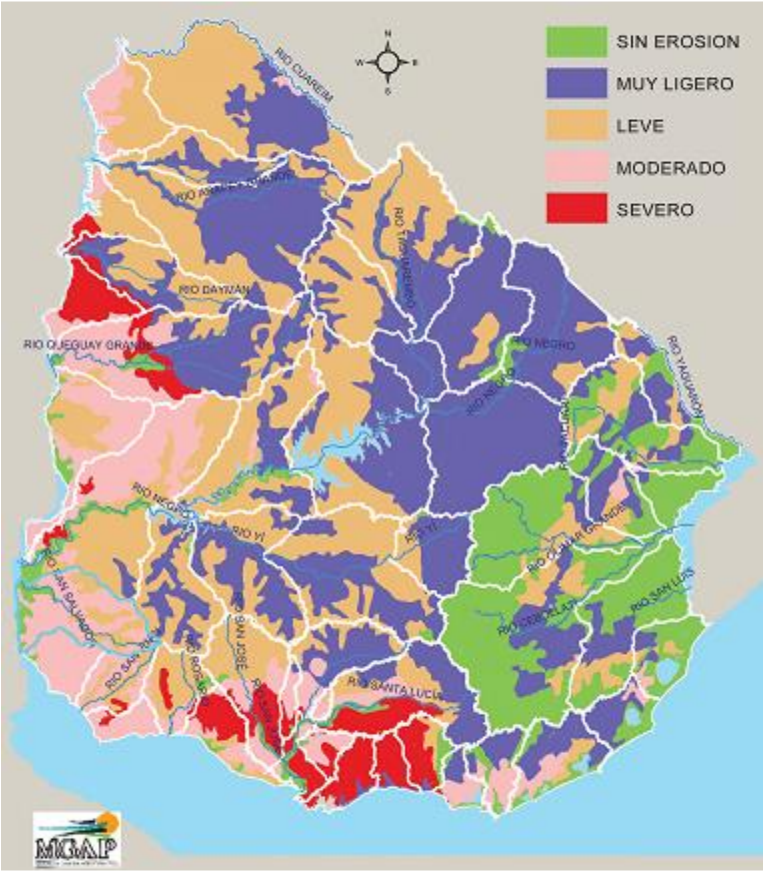


Figure 2. Erosion map of Uruguay (DINAMA/MGAP, 2005).
Explanation of colours: green = without erosion; blue = very mild erosion; orange = mild erosion; pink = moderate erosion; red = severe erosion.

The main cause of low income is that the vegetable crop yields of most producers is 50% or less compared to attainable yields in a region with similar resources and good management (Dogliotti et al., 2013). In addition there is a large variability in yield, quality of products and economic results between producers (Dogliotti et al., 2012). These differences are associated with the structure and functioning of the farm, soil management, crop rotation and management specifically for greenhouse tomatoes. The low yields are the major cause of low labour productivity, low resource use efficiency and high production costs per production unit (Dogliotti et al., 2012).

The five main horticultural crops in Uruguay are tomato, onion, sweet potato, carrot and sweet pepper. Their production volume is 116 million tons, which represent 72% of the total horticultural production of the country (DIEA/DIGERA, 2013). The Faculty of Agronomy (UdelaR) is currently carrying out a big project to reduce the yield-gaps of the major horticultural crops: tomatoes, onions and sweet potatoes. Tomatoes for fresh consumption account for 27% of the gross value of horticulture production in Uruguay, which is with 604 million Uruguayan pesos economically the most important horticultural crop for Uruguay (DIEA/DIGERA, 2013). In 2013, the South of Uruguay counts 418 tomato producers for fresh consumption, of which 236 producers grew the tomatoes in greenhouses (DIEA/DIGEGRA, 2013). These 236 producers together had a total greenhouse surface of 73 ha, which means that the average greenhouse surface per producer was 0.3 ha. Though, strong differences exist between producers. This might be linked to the difference in the implementation of production technology (DIEA/DIGERA, 2013). Production technology is defined as the complete set of agronomic inputs and production techniques (Van Ittersum and Rabbinge, 1997). Tomato yields in greenhouses fluctuated between 2002 and 2010 around 93 Mg/ha in the South of Uruguay, and in the season 2012-2013 yields reached 106 Mg/ha (DIEA/DIGERA, 2013). The attainable yield of greenhouse tomatoes according to experiments is not known but good producers in Uruguay exceed 200 Mg/ha with long production cycles.

1.3 Problem solving strategy

The first step to improve farm management and thereby yields is to understand what are the biophysical limitations of the crop related to yield. It is important to know what are the causes of the difference between actually reached yields by the producers and the potential yields according to agro-ecological conditions of the region. As well, the causes that determine the differences in yield between producers are important to know. The differences in yield can originate at several growing stages of the crop. It is important to know what are the consequences for the yield when stresses occur in each phenological stage.

Solanaceous species, of which tomato, consist of the following principal growth stages (Feller et al., 1995):

stage 0: Germination;
stage 1: Leaf development;
stage 2: formation of sides shoots;
stage 5: inflorescence emergence;
stage 6: Flowering;
stage 7: Development of fruit;

stage 8: Ripening of fruit and seed;
stage 9: Senescence

For growing tomatoes in greenhouses indeterminate varieties are used. Therefore the stages 2 until 9 happen simultaneously.

Yield is not the only and most important objective of producers. The decision making of producers can be influenced by profit maximization and risk aversion (Just, 1975; Lobell et al., 2009). Furthermore, because the society and producers may be concerned about the environmental impact and health, a trade-off might exist with yield (Matson et al., 1997). To understand the real causes of low yields, an approach should be used that combines the crop level with the farm level, the objectives of the farmers and their socio-economic context. Subsequently, solutions to the problems should be designed with the direct involvement of farmers in all stages to ensure relevance, applicability and adoption (Dogliotti et al., 2012).

The purpose of this thesis is to contribute to the reduction of the yield-gaps in greenhouse tomatoes in the South of Uruguay, by quantifying them and identifying their main causes. This thesis specifically aims to:

1. Quantify the yield-gaps in greenhouse tomato production.
2. Identify the major causes of variability in yield between producers.
3. Identify relationships between yield and the structural and functional characteristics of the farms of tomato producers.

In the following sections we will first describe methods that were used to investigate the yield-gaps and its causes. In chapter 3 results will be demonstrated. Chapter 4 will interpret the obtained results. Chapter 5 will describe the main conclusions and prospects for better methods to close yield-gaps.

2. Materials and Methods

In this section the step by step methodology will be explained that was used for this study. In the first section the selection of a representative sample of the total amount of greenhouse tomato producers in the South of Uruguay will be described. In the second section the procedure and the data that were collected from the sample will be demonstrated. The third section will show how the collected data were used for the analysis of the causes of yield-gaps. In the last section the statistical methods are described.

2.1 Selection of producers

In order to contribute to the sustainable development of horticultural family farms in the South of Uruguay, a representative sample of 10% of the total amount of greenhouse tomato producers was selected. From the database of the DIGEGRA Vegetable Survey a sample of 56 representative greenhouse producers was used, which is a statistically derived sample taken from the Census data by the DIEA. From these 56 producers, different types of producers were defined based on yield, total production and surface of greenhouse tomatoes. With assistance of local technical advisers, candidate farms were identified from each type.

2.2 Procedure and data collection for quantification of tomato yield-gaps

The methodological framework that has been applied to identify and rank the limiting factors for crop yield is the Regional Agronomic diagnosis (DAR) developed by Doré et al., (1997; 2008), and adapted by Berrueta et al. (2012) for processing tomatoes in the South of Uruguay. This method consists of regularly monitoring and doing a series of measurements in farms managed in the usual way by the producers themselves (Fermont et al. 2009).

The yield-gaps were quantified as the difference between the potential yield and the actual yields of farmers, expressed relative to the potential yield, with the formula $(1\text{-}Yield_{actual}/Yield_{attaimnable})*100$. Since neither experimental nor model-based information about potential yield of greenhouse tomatoes in the South of Uruguay is available, the average yield of the top 10% yielding crops (P90) will be considered as the attainable yield (Van Ittersum et al., 2013).

For diagnosis of the crop, an area with homogeneous management (one greenhouse) was selected, in order to monitor and evaluate the crop throughout the season through 2-weekly visits by the research team. The crop management activities done were registered by the producers in notebooks, which were reviewed on each visit to the farm. In the notebooks all the activities related to the crop were written down: irrigation time (the exact amount of water used for irrigation was measured by water flowmeters installed in each greenhouse), fertilizer applications, amendments, herbicides, fungicides, pesticides, soil tillage, weed control, plant handling, etc. The growth and development of the crop was estimated throughout the growing period by periodical monitoring of four randomly distributed plots inside each greenhouse. Each of the plots was two meters long along a ridge with tomato plants. Of each greenhouse the farmer registered the amount of crates with harvested tomatoes every week during the whole harvesting period. The yield was calculated by multiplying the total amount of full crates with the average weight of the crates.

Table 2 shows all the data that were measured in the greenhouses in order to investigate the causes of yield differences.

Table 2. Data collection of the variables that might cause differences in yield.

	Variable	Units	Description
Yield Determining Factors	CYCLE_LENGTH_SOWING	days	Cycle length since sowing
	CYCLE_LENGTH_TRANSPLANT	days	Cycle length since transplanting
	SIZE_GREENHOUSE	m^2	Greenhouse size
	DENSITY_PLANTING	plants m^{-2}	Plant density at transplanting
	DENSITY_START_HARVEST	plants m^{-2}	Plant density at the start of harvesting
	DENSITIY_FINAL	plants m^{-2}	Final plant density
	DEATH_PLANTS	plants m^{-2}	Death of plants at the end
	QUALITY_PLANTLET_HIGHT	cm	Height of plantlet
	QUALITY_PLANTLET_WIDE	cm	Leaf wide of plantlet
	QUALITY_PLANTLET_HEIGHT/WIDE	proportion	The proportion of plantlet height to plantlet wide
	QUALITY_PLANTLET_STEMDIAMETER	cm	Diameter of the stem of the plantlet
	QUALITY_PLANTLET_COVARIABLE	days after transplant	The moment the previous variables were measured
	LIGHT_BLOCKED_BY_CEILING	PAR	The difference in light from outside and inside the greenhouse
	TEMP_MEAN	°C	Mean daily temperature
	TEMP_MIN	°C	Minimum daily temperature
	TEMP_MAX	°C	Maximum daily temperature
	TEMP>30	hours/day	The average hours a day the temperature is above 30°C
	TEMP>35	hours/day	The average hours a day the temperature is above 35°C
	TEMP>40	hours/day	The average hours a day the temperature is above 40°C
	AVGE_THERMAL_SUM_DAY	°C.d	The average thermal sum a day
	%RH_MEAN	%	Mean daily relative humidity
	%RH_MIN	%	Minimum daily relative humidity
	%RH_MAX	%	Maximum daily relative humidity
	%RH>90	hours/day	The average hours a day the relative humidity is above 90%
	%RH<70	hours/day	The average hours a day the relative humidity is below 70%
	%RH<50	hours/day	The average hours a day the relative humidity is below 50%
	VARIETY	nominal	Variety (Lapataia, Valouro, Ichivan, Impala, Velocity, Torri, Badro)
	PLANT_PATTERN	nominal	The plant pattern of using a single row or a double row
Yield Limiting factors	SOIL_pH	pH	Soil pH measured before transplanting and fertilization
	SOIL_CE	mS/cm	Conductivity of the soil measured before transplanting and fertilization
	SOIL_COrg	%	Organic matter content in the soil measured before transplanting and fertilization
	SOIL_N-NO3	µg N/g	Nitrate in the soil measured before transplanting and fertilization
	SOIL_AVAILABLE_PHOSPHORUS	µg P/g	Available phosphorus in the soil measured before transplanting and fertilization
	SOIL_Ca	meq/100g	Calcium content in the soil measured before transplanting and fertilization
	SOIL_Mg	meq/100g	Magnesium content in the soil measured before transplanting and fertilization
	SOIL_K	meq/100g	Potassium content in the soil measured before transplanting and fertilization
	SOIL_Na	meq/100g	Natrium content in the soil measured before transplanting and fertilization
	MANURE_CHICKEN	kg m^{-2}	Added chicken manure before transplanting
	FERT_N	g m^{-2}	Total nitrogen added through fertigation
	FERT_P	g m^{-2}	Total phosphorous added through fertigation
	FERT_K	g m^{-2}	Total potassium added through fertigation
	FERT_Ca	g m^{-2}	Total calcium added through fertigation
	FERT_Mg	g m^{-2}	Total magnesium added through fertigation
	FERT_S	g m^{-2}	Total sulphur added through fertigation
	WATER	m^3	Total amount of water irrigated during whole growing cycle
	FOLIAR_SPRAYS	dichotomous	The application of foliar sprays (yes/no)
	MULCH	dichotomous	The use of plastic mulch (yes/no)
Yield Reducing factors	WHITEFLY_START	ordinal	The incidence of whiteflies at the start of harvesting
	POWDERY_MILDEW_START	ordinal	The incidence of powdery mildew at the start of harvesting
	MOTH_START	ordinal	The incidence of moths at the start of harvesting
	WILTING_START	%	The percentage of wilted plants at the start of harvesting
	WHITEFLY_END	ordinal	The incidence of whiteflies at the end
	POWDERY_MILDEW_END	ordinal	The incidence of powdery mildew at the end
	MOTH_END	ordinal	The incidence of moths at the end
	WILTING_END	%	The percentage of wilted plants at the end

Data on the structural and functional characteristics of the farms were collected from surveys that were done with all producers. The structural and functional characteristics were divided into different categories: general characteristics, production system, human resources, capital and water system (Table 3).

Table 3. Structural and functional characteristics of the farms, obtained by surveys.

General characteristics	Age of producers	
	Years of experience of producers	
	Total surface of land for cultivation (ha)	
	Total surface with greenhouses (m2)	
	Surface of tomato production (m2)	
	Principal crop(s)	
	Secondary crop(s)	
	Diversification	only tomato/number of greenhouse crops/number of field crops
	Commercialization	direct selling to retailers/through traders in the Montevideo central market/both
	Technical assistance	
	Objectives	keep it how it is/improve yield and quality/increase greenhouse surface/make investments/improve the commercialization/extend the offer period for tomatoes/increase profitability/improve farm organization
	Participation in organizations	no membership/membership but inactive/active participation
	Information access	(radio/neighbours/technical adviser/social organizations/sellers of inputs)
Production system	Conventional or organic	
	Types of cycles	(short/long/both)
Human resources	Employees from within the family	
	Permanent employees	
	Seasonal employees	
	Working hours a week of the producers during high-season	
	Amount of free days a year	
	Extra farm work	
Capital	Plant nursery	their own/commercial
	Tractor	
	Crop protection equipment	turbine/nebulizer/backpack turbine/backpack
	Type of fertigation	venture/injection pump/fertilization tank
	Transport	
	Cold room	

	Degree of mechanization	encanterador de discos/rotovador/ rotoencanterador/cincel
	Infrastructure for packaging	warehouse/packing/eaves
Water	Water source Capacity	well/excavated tank/reservoir/dam/creek

2.3 Analysis of major causes of yield differences among producers

It was intended to evaluate the response of the crop to environmental conditions and management by measuring yield and yield components. Yield components are variables that were directly measured in the crops. The yield component variables were focused on the growth, development, yield and quality of the product. Measurements were done every fifteen days on a sample of 8 plants per greenhouse. This means that from each of the four plots inside a greenhouse two plants were chosen for evaluation. For the yield all the performed harvests in the greenhouse during the cycle have been registered.

Yield components:

- Initial density (plants m^{-2})
- Density at the start of harvest (plants m^{-2})
- Dying of plants (plants m^{-2})
- Fruit size (kg/fruit)
- Number of fruits per m^2
- Number of fruits per plant
- Number of trusses per plant
- Number of fruits per truss
- Number of flowers per truss
- Fruit set (%)
- Cycle length (days)
- DNH ('Duración del número de hojas') refers to the cumulative amount of leaves during the growth cycle calculated by the formula: $DNH=\sum(((\text{Leaf number date}_{n1} + \text{Leaf number date}_{n2})/2)*\text{Days of interval}_{n2-n1})$

The rest of the variables surveyed and measured in the farms can be divided in yield determining factors, yield limiting factors and yield reducing factors, according to the classification proposed by Van Ittersum y Rabbinge (1997) and Van Ittersum et al. (2013).

Determining factors that result in the potential yield are:

- Planting date of the crop (seedlings and transplant)
- Growth duration of the crop (number of days)
- Density and planting pattern (evaluated at the transplanting, at the start of the harvest and at the end of the cycle)
- Temperature
- Relative humidity (RH%)
- Incident radiation
- Variety
- Quality of the plant at transplanting (length, wide and diameter of stem)

Characteristics of greenhouses that influence the environmental conditions were determined including orientation, slope location, surface, height, volume, age, type of polyethylene, type of ventilation and the use of wind shields. Temperature and relative humidity were monitored by sensors installed inside the greenhouses. The incident Photosynthetically Active Radiation (PAR) was determined by measuring the transparency of the greenhouse by taking measurements with a canopy analysis system (SunScan – Delta-T) inside and outside the greenhouse at midday.

Limiting factors that result in the attainable yield are:

- Physical characteristics of the soil: depth (not measured), texture of the soil layers, presence and depth of a compacted layer (not measured)
- Organic matter content (OM%)
- Chemical characteristics: pH, salinity and conductivity, nutrients
- Water balance of the crop: input by irrigation versus estimated demand throughout the cycle
- Nutrient inputs: organic and inorganic fertilizers, moments and dose

Reducing factors that result in the actual yield are:

- Competition with weeds
- Incidence and severity of diseases and pests

2.4 Statistical analysis

The sample of producers was selected through performing a cluster analysis on 56 representative farms that were obtained by the database of the Annual Vegetable Production Survey of DIEA (Dirección de Estadísticas Agropecuarias del Ministerio de Ganadería Agricultura y Pesca), in which yield (kg m^{-2}), total production (Mg) and surface of greenhouse (m^2) tomatoes were used as classifying variables. The producers were selected based on the frequency of each type of producers in the different zones in the South of Uruguay.

First descriptive statistics were used to describe the response variables yield and the yield components. The variables number of fruits per plant, number of flowers per plant, length of the growing cycle, death of plants, DNH, number of fruits per m^2, plant density at harvest and number of trusses per plant were transformed by logarithm (ln) to obtain Normally distributed variables. A path analysis was carried out, where yield was used as the dependent variable and the other factors were used as predictor variables. Through this analysis, the partitioning of direct and indirect factors on mean yield was obtained as standardized regression coefficients (Hannachi et al. 2013). The analysis was done with the CALIS procedure of the software program SAS/STAT 9.2 (SAS Institute, 2009).

To rank the effects of growth determining factors, limiting factors and reducing factors on yield first correlations between the different variables and yield were analysed. Because some variables were not Normally distributed, Spearman (non-parametric) correlations were calculated with the statistical program Infostat. Based on the p-values those variables were selected that were both significant on yield per m2 and yield per plant. In total 9 significant variables were selected for the CART (Classification And Regression Tree) analysis.

The nominal variables variety, planting frame, use of plastic mulch and use of foliar application could not be incorporated in the path analysis and therefore were analysed visually based on scatterplots.

As the sample size was too small to allow a statistical typology, relationships between yield level and structural and functional characteristics of the farms were investigated visually through scatterplots and column graphs.

3. Results

3.1 Sample selection

From the sample of 56 greenhouse tomato producers In the South of Uruguay, a cluster analysis was done. Three groups of greenhouse tomato producers were identified using yield (kg m^{-2}), total production (Mg) and surface of greenhouse tomatoes (ha) as classifying variables (Figure 3). Inside group 1, also three subgroups were identified (a, b, and c).

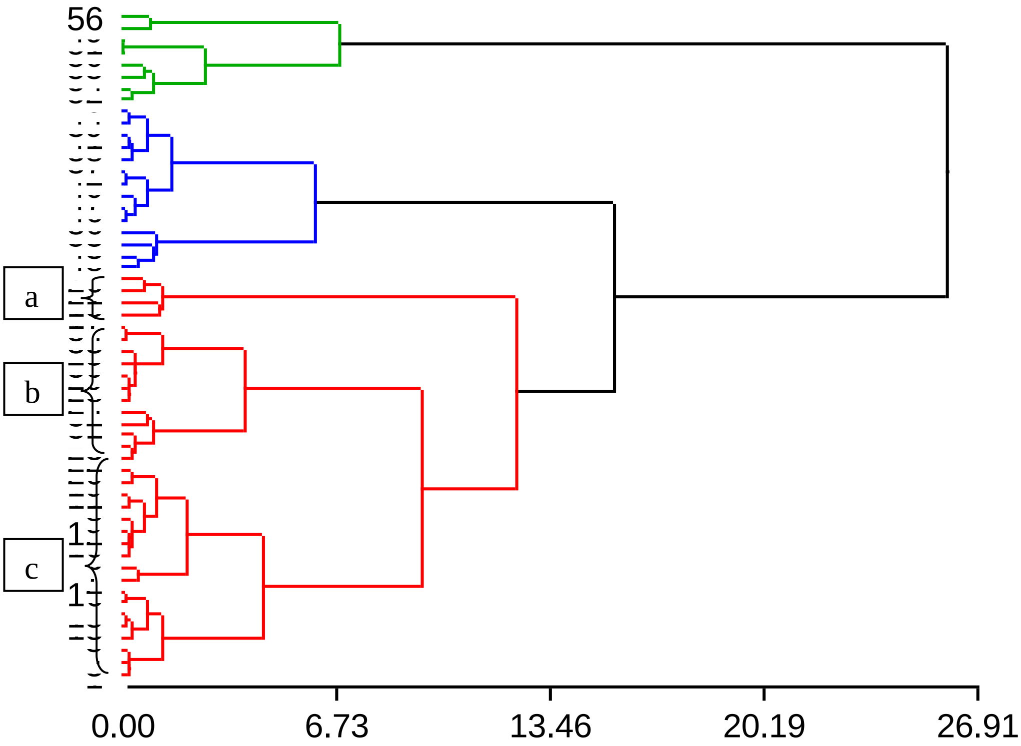


Figure 3. Cluster analysis presenting three groups: group 1 (red; below), group 2 (blue; middle) and group 3 (green; up). Group 1 was further divided into three subgroups (a, b and c). Ward method, Euclidean distance. Correlation: 0.506.

The characteristics of the groups that resulted from the cluster analyses are summarized in Table 4.

Table 4. Groups of different types of greenhouse producers according to previous cluster analysis.

Group	Variable	n	Mean	D.E.	CV (%)	Min	Max	Median
1	Yield (Kg/ha)	34	119554	41438	34	70000	240000	107941
1	Production (Mg)	34	32.11	19.69	61	5	80	29.78
1	Surface (ha)	34	0.28	0.16	58	0.05	0.6	0.21
2	Yield (Kg/ha)	14	50439	9955	20	25000	62500	51000
2	Production (Mg)	14	18.47	13.17	71	3	49.4	15
2	Surface (ha)	14	0.38	0.27	72	0.05	0.95	0.27
3	Yield (Kg/ha)	8	100156	14492	14	80000	120000	100000
3	Production (Mg)	8	112.31	34.47	31	75	161.5	110
3	Surface (ha)	8	1.14	0.4	35	0.8	1.9	1

It was investigated where the producers of each group were located. This is demonstrated for all groups in Table 5.

Table 5. The geographical distribution of producers, identified for each group separately.

Zone	**N° of producers in Group 1**	**N° of producers in Group 2**	**N° of producers in Group 3**
NE of Canelones	15	3	1
South of Canelones	8	5	2
Santoral	4	1	2
East of Canelones	4	1	1
Montevideo	0	1	2
San José	0	3	0
Florida	3	0	0

Combining all information, for each group representative producers were selected.

Group 1. Small producers (500 – 6000 m^2 of greenhouses) have the highest average yield (119 Mg ha^{-1}), however, very variable (70 to 240 Mg ha^{-1}). This groups represents 61% of the analysed farms.

Subgroup a. Consists of 4 producers (7% of the total) characterized by the highest yields (more than 190 Mg ha^{-1}). Located in the South and North-East (NE) of Canelones. 2 producers were selected: 1 in the North East of Canelones and 1 in the South of Canelones.

Subgroup b. Consists of 12 producers (22% of the total) characterized by greenhouse surfaces of 3200 – 3000 m^2 and yields between 83 and 140 Mg ha^{-1}. Mainly located in the NE of Canelones, and some in the South of

Canelones. 5 producers were selected: 3 in the NE of Canelones, 1 in the South of Canelones and 1 in Santoral.

Subgroup c. Consists of 18 producers (32% of the total) characterized by small greenhouse surfaces (500 – 3000 m^2) and yields between 70 and 160 Mg ha^{-1}. Mainly located in the North-East of Canelones (40%), South of Canelones and Santoral. 7 producers were selected: 3 in the NE of Canelones, 2 in the South of Canelones and 2 in Santoral.

Group 2. Small to average producers (500 – 9500 m^2 of greenhouses) that reach very low yields (25 to 62.5 Mg ha^{-1}). This group represents 25% of the analysed farms. 6 producers were selected: 1 in the NE of Canelones, 3 in the South of Canelones and 2 in San José.

Group 3. Big producers (8000 – 19000 m^2 of greenhouses) with medium to high yields (average 100 Mg ha^{-1}). This groups represents 14% of the analysed farms. 3 producers were selected: 1 in the South of Canelones, 1 in Santoral and 1 in the South of Canelones.

Looking at Figure 4 where yield is plotted against surface of greenhouses, we can observe the three groups and the subgroups inside group 1:

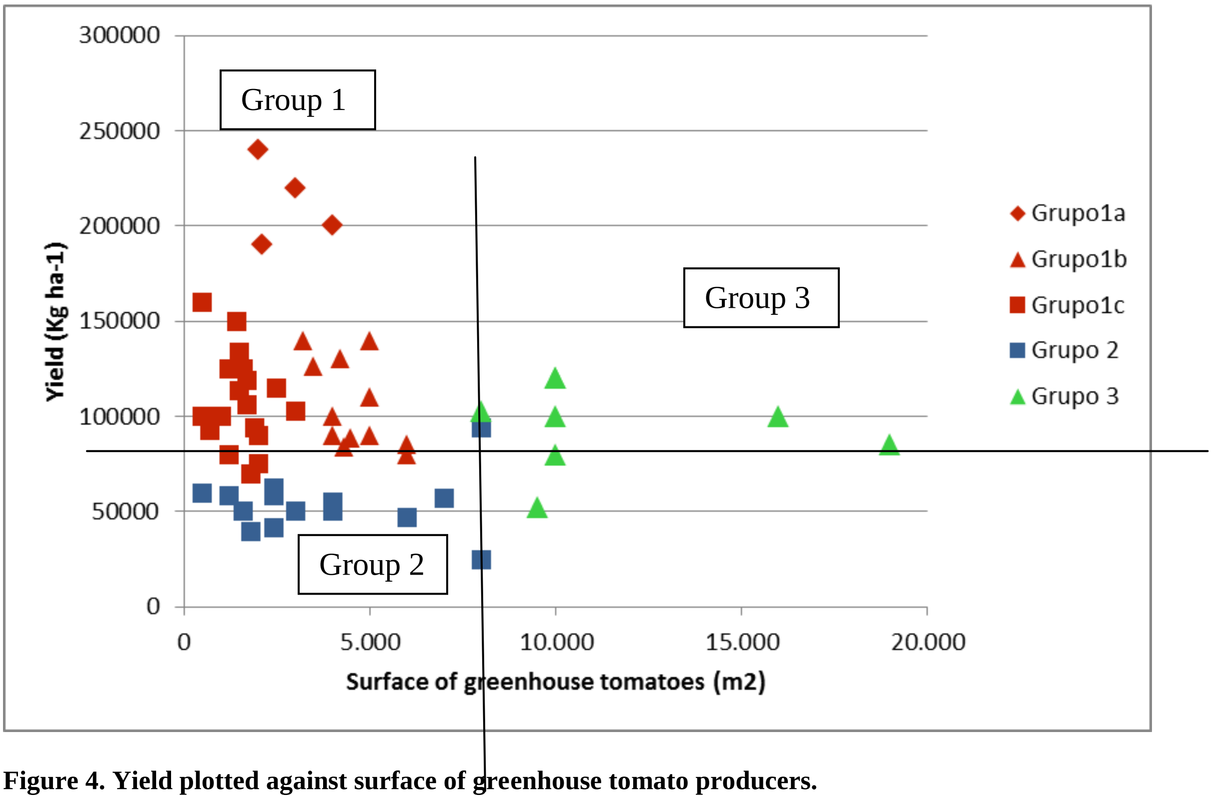


Figure 4. Yield plotted against surface of greenhouse tomato producers.

In total 23 farms were selected. In this study 18 of them were taken into account for the analysis. In each of the 18 selected farms, 1-3 crops were selected which resulted in monitoring a sample of 22 crops.

3.2 Quantification of the yield-gap

A high variability in yields was observed in the sample of 22 tomato crops (Figure 5). Maximum yield was 20.1 kg m^{-2} and minimum yield was 0 kg m^{-2} as one crop died by bacterial cancer (*Clavibacter michiganensis subsp. Michiganensis)* before harvesting. Average yield was 9.4 kg m^{-2}.

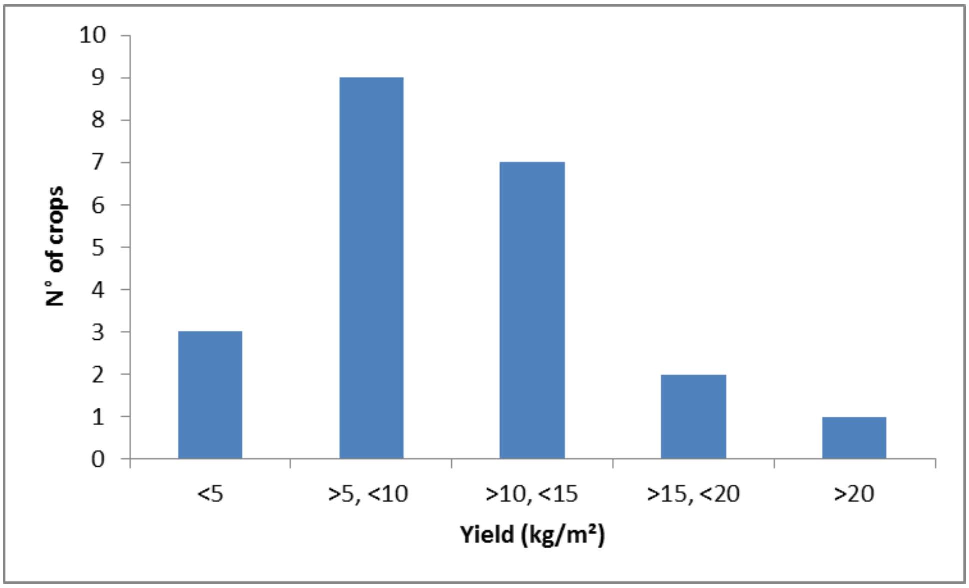


Figure 5. The number of crops according to a yield range.

Maximum yield was calculated from the top 10% yielding crops (P90) in the sample, which resulted in a potential yield of 18.1 kg m^{-2} and 8.7 kg per plant.

The average yield-gap was estimated by the formula $(1-Yield_{actual}/Yield_{attainable})*100$. The average yield-gap is estimated at 48% based on yield per m^2 and 54% based on yield per plant (Table 6).

Table 6. Average yield and the yield-gap.

N	Yield per surface (kg m^{-2})	Average yield-gap	Yield per plant (kg/plant)	Average yield-gap
22	9.4 ± 4.6	48%	4.0 ± 2.2	54%

3.3 Major causes of variability in yield

First the yield was ranked based on the yield components. With these yield components a path analysis was done to identify the mayor components that explain the differences in yield (Figure 6).

Yield was significantly related to the number of fruits per m2, and a lesser extent to the size of the fruits. The number of fruits per m^2 was strongly associated with the number of fruits per plant. Number of fruits per m2 was also related to plant density at harvest, but less strongly than to number of fruits per plant. Plant density at harvest was positively related to initial plant density. Plant density at harvest was also negatively related to the death of plants, but less strongly than initial plant density. Number of fruits per plants was strongly associated with the number of trusses per plant. Number of fruits per truss was also related to the number of fruits per plant, but less strongly than to the number of trusses per plant. The number of fruits per truss was equally explained by number of flowers per truss and fruit set. The number of trusses per plant was explained by the length of the growing cycle.

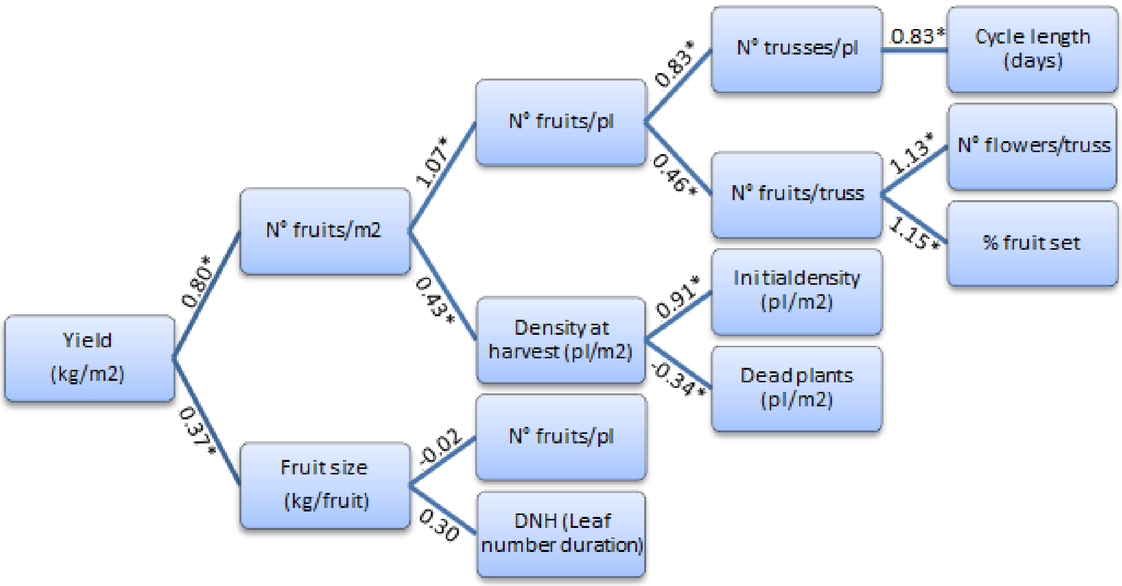


Figure 6. Path analysis with yield components. Arrows indicate direct effects. * p-value<0,05

Spearman correlations between variables describing the production and management system on the one hand and yield per area and per plant on the other are shown in Table 7. Based on significances in correlations, the following 9 variables were selected: cycle length since sowing, cycle length since transplanting, size of the greenhouse, death of plants, hours a day of relative humidity under 50%, soil available N-NO3 (before fertilizing), addition of chicken manure, added nitrogen by fertigation and added potassium by fertigation. These 9 variables were used in the CART analysis.

Table 7. Spearman correlations with p-values in red for those variables that were both significant on yield per m2 and yield per plant. Correlations are significant if p-value ≤ 0,05.

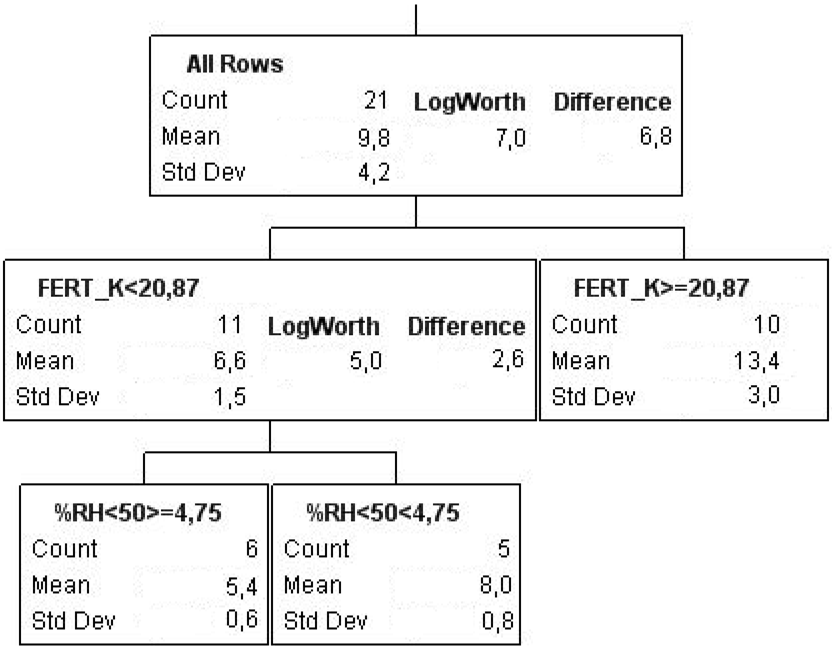
		YIELD kg m^{-2}		YIELD kg/plant	
		correlation	p-value	correlation	p-value
Yield Determining Factors	**CYCLE_LENGTH_SOWING**	**0,67**	**6,30E-04**	**0,71**	**2,00E-04**
	CYCLE_LENGTH_TRANSPLANT	**0,66**	**9,20E-04**	**0,71**	**1,90E-04**
	SIZE_GREENHOUSE	**-0,44**	**0,04**	**-0,47**	**0,03**
	DENSITY_PLANTING	-0,23	0,29	-0,42	0,05
	DENSITY_START_HARVEST	-0,18	0,42	-0,38	0,08
	DENSITIY_FINAL	0,13	0,56	-0,05	0,8
	DEATH_PLANTS	**-0,49**	**0,02**	**-0,47**	**0,03**
	QUALITY_PLANTLET_HIGHT	0,11	0,62	0,11	0,63
	QUALITY_PLANTLET_WIDE	-0,01	0,98	-0,05	0,83
	QUALITY_PLANTLET_HEIGHT/WIDE	0,05	0,83	0,07	0,77
	QUALITY_PLANTLET_STEMDIAMETER	0,02	0,93	-0,02	0,94
	QUALITY_PLANTLET_COVARIABLE	0,16	0,48	0,27	0,23
	LIGHT_BLOCKED_BY_CEILING	0,08	0,72	0,16	0,47
	TEMP_MEAN	-0,01	0,97	0,01	0,98
	TEMP_MIN	0,12	0,6	0,14	0,54
	TEMP_MAX	-0,18	0,43	-0,19	0,41
	TEMP>30	-0,14	0,55	-0,15	0,52
	TEMP>35	-0,1	0,66	-0,07	0,76
	TEMP>40	-0,32	0,16	-0,28	0,22
	AVGE_THERMAL_SUM_DAY	0,33	0,16	0,3	0,2
	%RH_MEAN	0,42	0,06	0,29	0,19
	%RH_MIN	0,44	0,05	0,39	0,08
	%RH_MAX	0,44	0,04	0,33	0,14
	%RH>90	0,31	0,17	0,17	0,47
	%RH<70	-0,37	0,1	-0,28	0,21
	%RH<50	**-0,59**	**0,01**	**-0,52**	**0,02**
Yield Limiting factors	SOIL_pH	0,06	0,79	-0,09	0,69
	SOIL_CE	0,35	0,11	0,39	0,07
	SOIL_COrg	0,08	0,71	0,19	0,39
	SOIL_N-NO3	**0,45**	**0,04**	**0,55**	**0,01**
	SOIL_AVAILABLE_PHOSPHORUS	0,05	0,83	-0,06	0,8
	SOIL_Ca	-0,12	0,6	-0,05	0,84
	SOIL_Mg	-0,15	0,5	-0,12	0,58
	SOIL_K	0,26	0,24	0,31	0,16
	SOIL_Na	0,29	0,19	0,44	0,04
	MANURE_CHICKEN	**0,41**	**0,05**	**0,56**	**0,01**
	FERT_N	**0,6**	**3,00E-03**	**0,59**	**4,10E-03**
	FERT_P	0,11	0,61	0,08	0,73
	FERT_K	**0,83**	**1,50E-06**	**0,81**	**5,40E-06**
	FERT_Ca	0,38	0,08	0,47	0,03
	FERT_Mg	0,05	0,84	-0,00058	1
	FERT_S	0,09	0,68	0,05	0,83
	WATER	0,17	0,45	0,18	0,42

Yield Reducing factors	WHITEFLY_START	-0,22	0,32	-0,24	0,28
	POWDERY_MILDEW_START	-0,45	0,03	-0,35	0,11
	MOTH_START	0,13	0,56	0,2	0,38
	WILTING_START	-0,43	0,05	-0,37	0,09
	WHITEFLY_END	-0,15	0,5	-0,17	0,46
	POWDERY_MILDEW_END	-0,38	0,08	-0,28	0,21
	MOTH_END	0,23	0,29	0,34	0,12
	WILTING_END	-0,44	0,04	-0,38	0,08

The CART analyses with each yield variables (expressed in kg m^{-2} and kg plant^{-1}) resulted in the same factors that explained the differences in yield. Firstly, differences in yield were explained by the amount of potassium added through fertigation during the growing cycle (FERT_K). Higher total input of potassium by fertigation resulted in a higher yield. Subsequently, the group with low potassium input was divided by the average number of hours per day the relative humidity was under 50% (%RH<50). A larger number of hours a day with a relative humidity under 50% resulted in a lower yield.

According to the CART analysis for yield per square meter the highest yields (average 13.4 kg m^{-2}) were obtained when 20.9 g m^{-2} or more of potassium was added through fertigation during the growing cycle (Figure 7). Medium yields (average 8.0 kg m^{-2}) were obtained when less than 20.8 g m^{-2} potassium was added, and when relative humidity was under 50% during less than 4.75 hours a day. Lowest yields (average 5.4 kg m^{-2}) were obtained when less than 20.8 g m^{-2} potassium was added and when relative humidity was under 50% during more than 4.75 hours a day.

Figure 7. Regression tree as a result from the CART analysis with yield expressed as kg m-2.

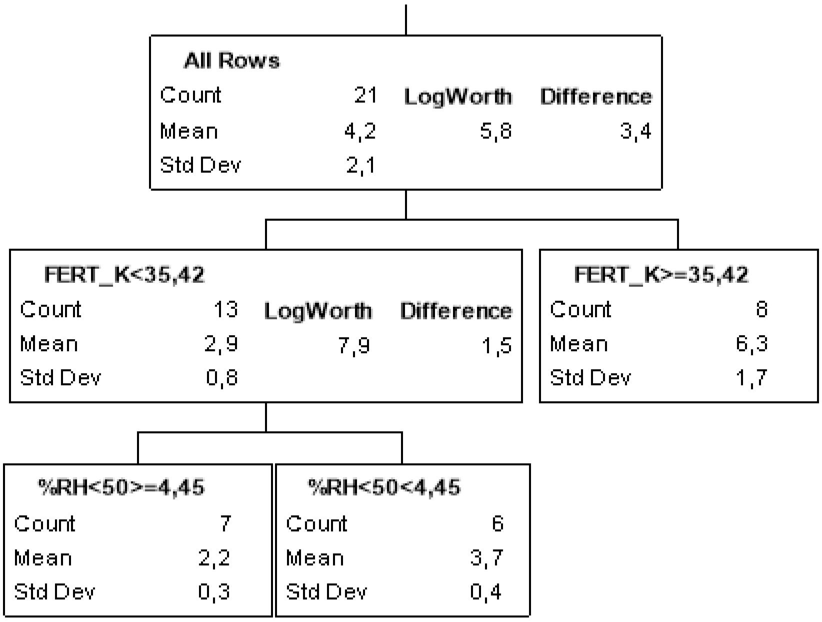


RSquare	N	Number of Splits	Significance
0,749	21	2	If LogWorth* ≥ 1.3 then p-value ≤ 0,05

*** LogWorth= -log10*(p-value)**

According to the CART analysis for yield per plant the highest yields (6.3 kg plant^{-1}) were obtained when 35.4 g m^{-2} or more of potassium was added through fertigation during the growing cycle (Figure 8). Medium yield (average 3.7 kg plant^{-1}) was obtained when less than 35.4 g m^{-2} potassium was added, and when the relative humidity was under 50% during less than 4.4 hours a day. Lowest yields (average 2.2 kg plant^{-1}) were obtained when less than 35.4 g m^{-2} potassium was added and when relative humidity was under 50% during more than 4.4 hours a day.

Figure 8. Regression tree as a result from the CART analysis with yield expressed as kg plant-1.



RSquare	N	Number of Splits	Significance
0,740	21	2	If LogWorth* ≥ 1.3 then p-value ≤ 0,05

***LogWorth= -log10*(p-value)**

The nominal variables could not be incorporated in the CART analysis and therefore were analysed from bar graphs. There were no significant differences found related to the nominal variables.

In order to know if the amount of potassium added by the producers was sufficient or insufficient, the total added potassium by the producers was compared to literature data about nutrient needs of tomatoes. Table 8 shows the amount of nutrients in kilograms that should be added dependent on the expected yield in tons of harvested product. In this case not the expected yield but the final yield of each crop was used to calculate the potassium needs, expressed as the minimum recommended and maximum recommended potassium. At the other hand the total applied potassium by the producers was calculated from the sum of start fertilization (by manure, compost and synthetic fertilizer) and fertilization during crop growth by fertigation. The minimum recommended potassium, the maximum recommended potassium and the total added potassium were calculated and compared for every crop separately (Figure 9).

Table 8. Nutrient needs of tomatoes according to the expected yield in tons (Castilla, 1995)

	kg per ton of harvested product
N	2,1-3,8
P2O5	0,7-1,6
K2O	5,3-8,4
Ca	1,2-3,2
Mg	0,3-1,1

It turned out that to two crops more than the maximum recommended potassium was added, to six crops the right amount of potassium was added, and to twelve crops less than the minimum recommended potassium was added. One crop died off before harvest and therefore no potassium recommendations could be calculated based on the yield.

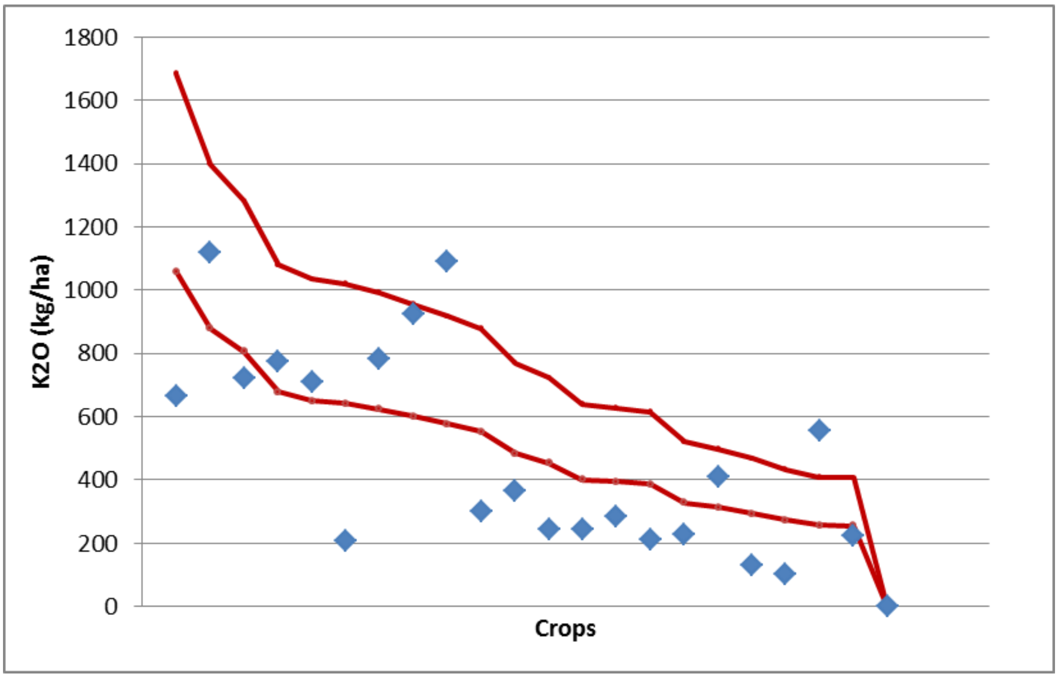


Figure 9. The total amount of potassium (K_2O) added by the producers for each crop (dots) in comparison with the minimum and maximum recommended potassium (lines). If the right amount of potassium was applied, the dots are placed in between the minimum and maximum lines.

The same procedure was done to test if the amount of nitrogen added by the producers was sufficient or insufficient. It turned out that to five crops more than the maximum recommended nitrogen was added, to ten crops the right amount of nitrogen was added, and to six crops less than the minimum recommended nitrogen was added (Figure 10). One crop died off before harvest and therefore no nitrogen recommendations could be calculated based on the yield.

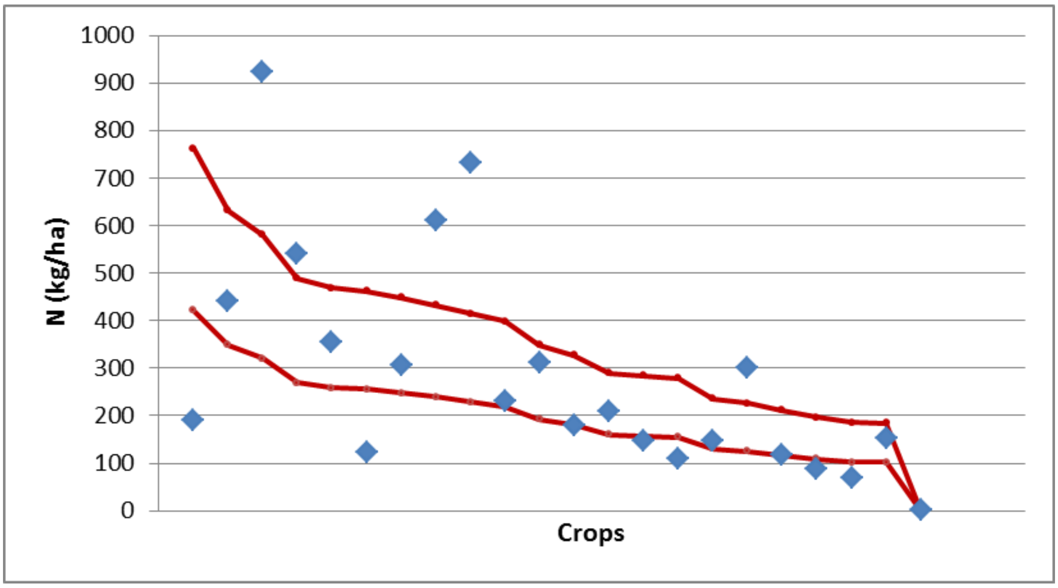


Figure 10. The total amount of nitrogen (N) added by the producers for each crop (dots) in comparison with the minimum and maximum recommended potassium (lines). If the right amount of potassium was applied, the dots are placed in between the minimum and maximum lines.

3.4 Yield in relation to the structural and functional characteristics of the farms

Producers that are specialized to work with long cycles obtain a significant higher yield than producers that work with short cycles or both cycles (Figure 11). If a producer works with both cycles this means that the producer did not specialized on long or short cycles. The two highest yields obtained in this investigation were obtained by the two producers that were specialized in working with long cycles.

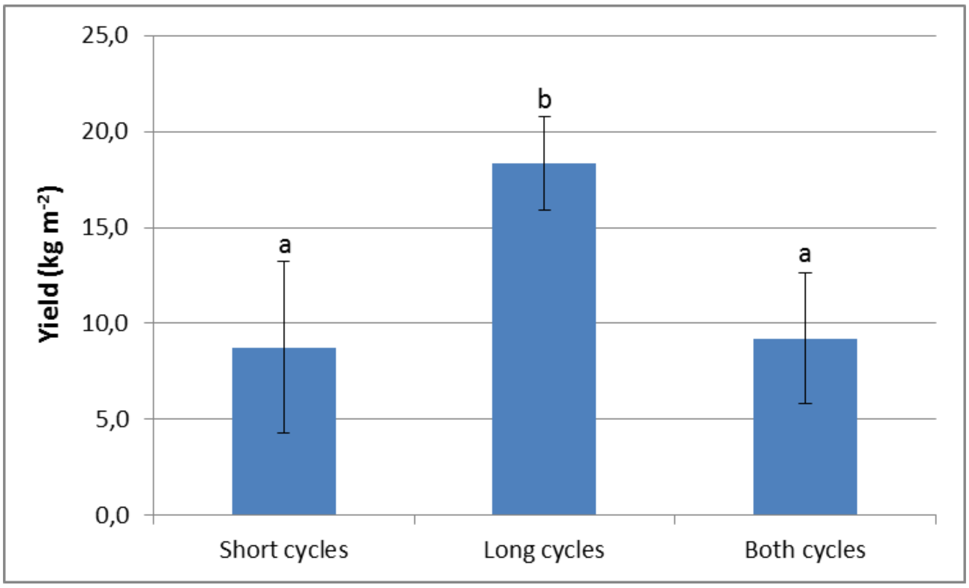


Figure 11. Yield in relation to the type of cycles normally used by the producers. Bars represent the standard deviation, bars with the same letter on top do not differ significantly, n=18.

A further division was made of the producers that work with both cycles into a group that performed a long cycle during the study and a group that performed a short cycle during the study (Figure 12). Still, the producers that were specialized in long cycles obtained a higher yield than the producers that were not specialized but also performed a long cycle during the study. Inside the unspecialized group of producers no significant difference was found between the use of long and short cycles.

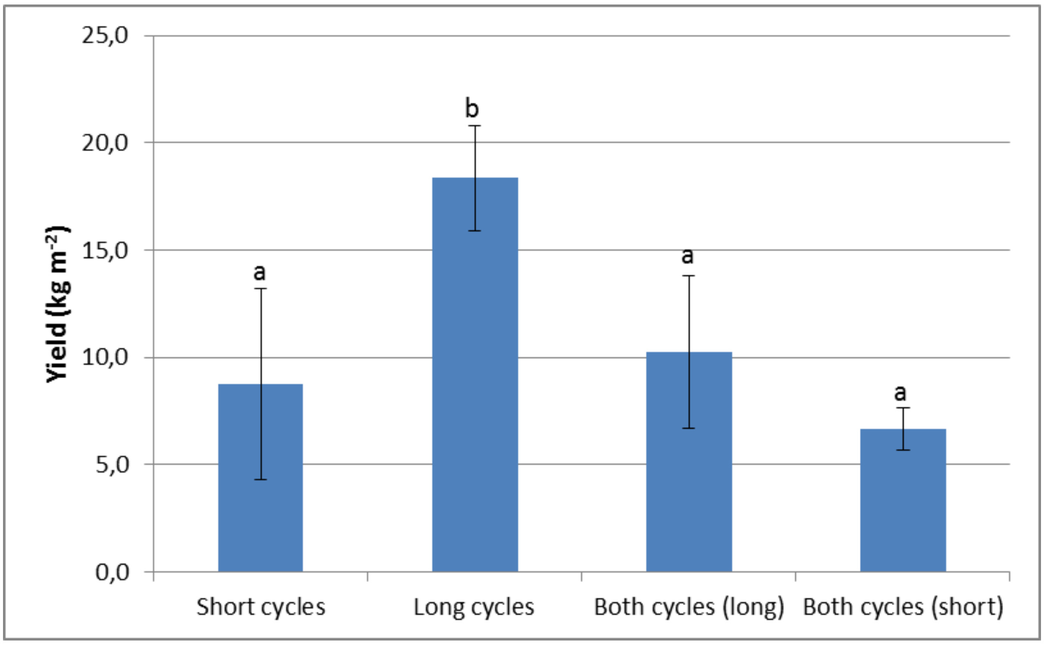


Figure 12. Yield in relation to the type of cycles normally used by the producers . Bars represent the standard deviation, bars with the same letter on top do not differ significantly, n=18 (same data as in Figure 10, but 'both cycles' divided in short and long cycles according to the cycle they used during this study).

There seemed to be a negative tendency between years of experience and yield (Figure 13). More experience would result in a lower yield. However, the R squared of 0.0925 is rather low. Also the slope of the regression line is not significantly different from zero (p=0.22).

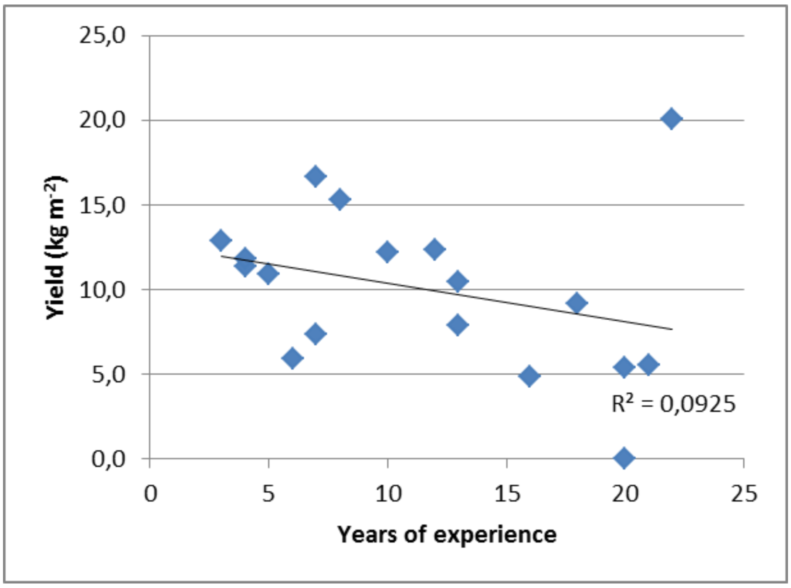


Figure 13. Relation between years of experience and yield. Since p-value = 0.22 > 0.05 the slope of the regression line is not significantly different from zero.

Test	RSquare	n	p-value	α	t-value	t_{crit}	Significance
t-test	0,0925	18	0.22	0.05	1.28	1.75	no

In this particular case, the outlier only represents the years of experience of the main producer. However his parents, wife, son and daughter were also full-time working in the greenhouses, but their years of experience were not taken into account. When removing this outlier, a clearer tendency appears with a higher R squared of 0.4266 (Figure 14). The slope of this regression line is significantly different from zero (p=0.0045)At the same time, no relationship at all was found between yield and the age of the producers (R2=0.0087).

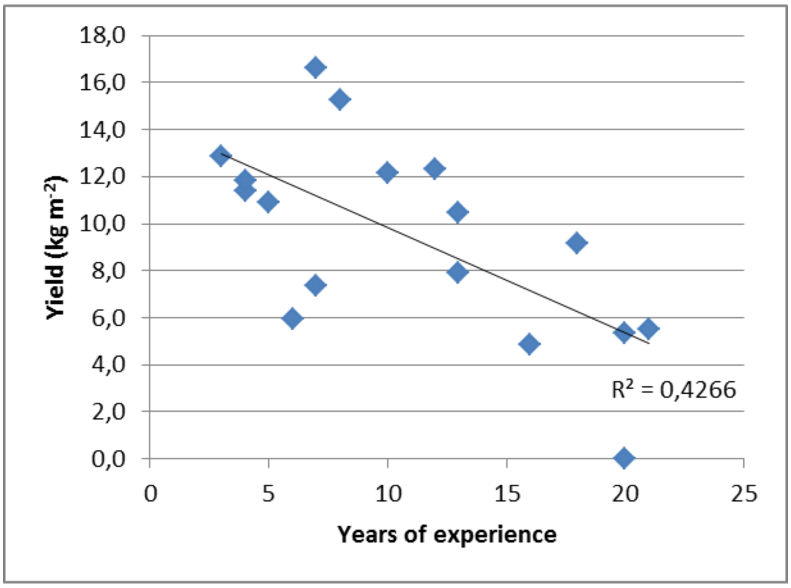


Figure 14. Negative tendency between years of experience and yield (same data as in Figure 11, outlier removed). Since p-value = 0.0045 < 0.05 the slope of the regression line is significantly different from zero.

Test	RSquare	n	p-value	α	t-value	t_{crit}	Significance
t-test	0,4266	17	0.0045	0.05	3.34	1.75	yes

No other relationships were found between yield and structural and functional characteristics of the farms.

4. Discussion

4.1 Quantification of the yield-gap

For the 22 evaluated greenhouse tomato crops in the South of Uruguay an average yield of 9,4 kg m^{-2} was calculated, which corresponds to 94 Mg/ha. This outcome is very similar to the 93 Mg/ha that was obtained in surveys between 2002 and 2010 in the same region (DIEA/DIGERA, 2013). This could be an indication that a representative sample of the total number of producers was taken.

In comparison, in the Netherlands the average tomato yield in 2012 was 47 kg m^{-2} (Centraal Bureau voor de Statistiek [CBS] 2013, FAOSTAT 2015) . The Netherlands is registered as having the highest average tomato yield of the world between 2000 and 2013 (FAOSTAT 2015). However, the very high-input system of the Netherlands with greenhouses of glass is not a very suitable reference when searching for yield improvement without increasing costs. A better comparison could be made with Almeria, the horticultural centre of Spain, where similar production systems are used with plastic greenhouses. The average yield of tomato producers in Almeria is 15 kg m^{-2}, with a maximum yield of 22 kg m^{-2} with long production cycles and without heating (personal communication Manuel Hernandez Fernandez, tomato crop specialist in Rijk Zwaan Iberica), which is very similar to the maximum yield reached in Uruguay. However, in Uruguay major differences in yield occur between producers as the average yield-gap of this investigation was 48%. Emphasis for yield increase should be on the producers with big yield-gaps.

4.2 Length of the growing cycle

The yield component that explained more of the differences in yield was the length of the growing cycle (Figure 6). This is a logical outcome as production increases with more days of cultivation of the tomato crop. There were large

differences between growing cycle lengths. The shortest cycle comprised 116 days after transplanting, and the largest cycle included 229 days which is almost de double number of days, and that implies a big difference in yield. The main reason for these big differences in cycle length is that some producers prefer to do two short cycles instead of one large one. The producers mentioned that the main reason for choosing for two short cycles is the ease of handling of crop health. In further research the crops of producers that do two consecutive short cycles should be evaluated as if it would be one large one. It would be interesting to compare if two short cycles together obtain a similar yield as one large cycle.
There were also some producers that had the intention of doing a short cycle but ended up doing a large cycle. Their practice was to continue harvesting the tomatoes but without doing any more management activities except of irrigation. This practice increases disease and pest pressure and might, on the long term, not pay off the extra yield.

4.3 Potassium fertigation

The CART analysis gave as outcome that potassium fertilization by fertigation was the most important factor causing differences between yields (Figure 7, Figure 8). Surprisingly, the outcome of the CART analysis did not give the outcome that cycle length was an influencing factor on yield, while in the path analysis cycle length was the most important factor.

Potassium (K) is one of the three major elements that plants need. Greenhouse tomatoes have a very high potassium requirement for growth and fruit production. Potassium plays an important role in plant processes as cell turgor, enzyme activation, photosynthesis, protein synthesis, ion homeostasis in plant cells and transportation of assimilated products (Lin, 2010, Kanai et al., 2011). Potassium deficiency can disturb these plant processes directly, which results in the restriction of assimilate partitioning to the sink from the source. When potassium deficiency occurs, normally there are no immediate visible symptoms. First the growth of the plant decreases and it gradually stops. Only after prolonged potassium deficiency visible symptoms appear like leaf necrosis (Besford, 1978). A possible method for monitoring the potassium status during crop growth is the use of quick petiole sap K tests (Coltman and Riede, 1992).

Big differences were found between amounts of potassium application through fertigation. The lowest amount of potassium added through fertigation was 5 g m^{-2}, in contrast, the highest amount potassium added was 71.7 g m^{-2}. Fertilizer application by fertigation, results in a higher fertilizer-use efficiency than by surface application in dry form, as the fertilizer is applied directly into the zone of maximum root activity. Compared with traditional methods it has been demonstrated that fertigation saves fertilizer and water use and simultaneously increases tomato yield (Hebbar et al. 2004).

Compared with general recommendations on K application, 13 out of 21 crops received less potassium than the minimum recommended amount of potassium (Figure 9). In contrast, only 6 crops received less nitrogen than the minimum recommended amount of nitrogen, and 5 producers were over fertilizing (Figure 10). Moreover, application of the right total amount of fertilizer should be accompanied by appropriate timing of application. On average about 48% of the total added potassium was applied before transplanting, the other 52% was applied during crop growth through fertigation. In case of nitrogen even 67% of the total added nitrogen was applied before transplanting. It is necessary to reduce the proportion of start fertilization and increase the proportion added by fertigation, this is even more important when applying nutrients that are susceptible to leaching, like nitrogen and potassium, and those that are susceptible to be retained like phosphorus and potassium (Molina et al., 1993). When soil potassium levels are high before transplanting, it is even possible to not apply any start fertilization and distribute the total recommended potassium equally over the following three stages: one week after transplanting, when first fruits are 2.5 cm in diameter, and when first fruits turn colour (Reiners et al. 1991). There is room for improvement in the actual nutrient management, not only to increase yield, but also to reduce fertilizer costs and environmental burden.

4.4 Relative Humidity under 50%

The CART analysis revealed that the group with low potassium application (< 20.8 g m^{-2}) could be further divided into two groups based on the number of hours a day on which the relative humidity (RH) was under 50%. The reduction in yield because of low relative humidity only occurred when there was a potassium deficit as well. This is a logical outcome as potassium is essential for plant cell turgor and osmosis.

In general, the optimum RH for growth, flowering, fruit set and fruit growth of tomato plants is between 65% and 75% (Bakker, 1991a). In literature, RH expressed as percentage is not commonly used. Humidity can be expressed in two other variables that take into account the influence of the temperature: absolute humidity (g/m3) or specific humidity (g water/kg air). Temperature is a key factor as it influences the amount of water vapour that a certain volume of air can hold. When the difference increases between the fully saturated water vapour inside the leaf (100% RH) and the water vapour in the outside air, transpiration rate increases. This difference between water vapour in the leaf and water vapour in the surrounding air is expressed as the vapour pressure deficit (VPD) (Peet, 2005). VPD is expressed in the units millibars (mbar) or kilopascals (kPa). The optimal VPD for nutrient uptake and photosynthesis is between 4 and 8 mbar (Table 9).

Table 9. Vapour pressure deficit in millibars (mbar) in relation to temperature and humidity (Source: Peet, 2005). The bold area indicates the optimal range for most greenhouse crops.

Temperature (°C)[a]	Relative humidity									
	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
15	8.5	**7.7**	**6.8**	**6.0**	**5.1**	**4.3**	3.4	2.6	1.7	0.8
16	9.1	8.2	**7.3**	**6.4**	**5.5**	**4.6**	3.6	2.7	1.8	0.9
17	9.7	8.7	**7.8**	**6.8**	**5.8**	**4.9**	3.9	2.9	1.9	1.0
18	10.3	9.3	8.3	**7.2**	**6.2**	**5.2**	**4.1**	3.1	2.1	1.0
19	11.0	9.9	8.8	**7.7**	**6.6**	**5.5**	**4.4**	3.3	2.2	1.1
20	11.7	10.5	9.4	8.2	**7.0**	**5.9**	**4.7**	3.5	2.3	1.2
21	12.4	11.1	9.9	8.7	**7.5**	**6.2**	**5.0**	3.7	2.5	1.2
22	13.2	11.9	10.6	9.3	**7.9**	**6.6**	**5.3**	**4.0**	2.6	1.3
23	14.1	12.6	11.2	9.8	8.4	**7.0**	**5.6**	**4.2**	2.8	1.4
24	14.9	13.4	11.9	10.4	9.0	**7.5**	**6.0**	**4.5**	3.0	1.5
25	15.8	14.3	12.7	11.1	9.5	**7.9**	**6.3**	**4.8**	3.2	1.6
26	16.8	15.1	13.4	11.8	10.1	8.4	**6.7**	**5.0**	3.4	1.7
27	17.8	16.0	14.2	12.5	10.7	8.9	**7.1**	**5.4**	3.6	1.8
28	18.9	17.0	15.1	13.2	11.3	9.5	**7.6**	**5.7**	3.8	1.9
29	20.0	18.0	16.0	14.0	12.0	10.0	8.0	**6.0**	**4.0**	2.0
30	21.2	19.1	17.0	14.8	12.7	10.6	8.5	**6.4**	**4.2**	2.1

[a] refers to plant tissue temperatures
1 mbar = 0.1 kPa
0.1 kPa = 0.7 g/m^3 = 3% RH

At a low humidity (high VPD), the transpiration may be excessive. This can lead to morphological and physiological changes like an increase of dry matter content, and a decrease of leaf area (Schwarz et al. 2014; Heuvelink and Dorais, 2005). Pollen number, pollen vigour and pollen germination rate as well can be negatively affected by low relative humidity in combination with high temperatures (Huang et al. 2011; Harel et al. 2014). A very low relative humidity may result in water stress and therefore (partial) stomatal closure (Heuvelink and Dorais, 2005). With the stomata closed, photosynthesis is reduced which may lead to a plant growth reduction (Bakker, 1991b). However, photosynthesis reduction because of low relative humidity only takes place if plants are stressed by a high EC root environment or water deficit (Heuvelink and Dorais, 2005). A side-effect of low relative humidity in combination with high temperatures is that it promotes the propagation of harmful insects like spider mites (*Tetranychidae*) and white fly (*Trialeurodes vaporariorum*) (Schwarz, 2014).

The first adaptation towards better control of relative humidity is to place sensors in the greenhouses in order to be able to monitor. The temperature and humidity in the greenhouses in Uruguay were controlled by opening and closing the sides of the greenhouses. Therefore, the most straightforward solution for increasing the relative humidity would be to close the sides of the greenhouse. However, this might be associated with a temperature increase so the VPD would not necessarily decrease. Therefore, especially in summer time, shade nets or white paint could be placed on top of the greenhouse roofs. Other solutions for avoiding the negative effects of low humidity include adjusted irrigation, the use of wet-pads, fogging and misting systems (Schwarz, 2014; Harel et al., 2014).

4.5 Functional and structural characteristics of the farms

The results indicate that producers that are specialized to work with long production cycles obtained a significantly higher yield than producers that work with short cycles or both cycles (Figure 11). This outcome corresponds with the result from the path analysis, where cycle length was the most important yield-component (Figure 6). Producers that work with both cycles and performed a long cycle for this study obtained a lower yield than the specialized long cycle producers (Figure 11). This might be related to a worse crop planning than the specialized producers. Some producers let the crop die off, in order to continue the harvest and at the same time reduce labour and inputs. This practice might be linked to the continued warm weather after summer, which allowed the crops to produce during more time than initially expected. In further studies clear notes should be taken about the practice of letting the crop die off and its duration.

A negative tendency was found between years of experience and yield (Figure 14), meaning that more years of experience resulted in a lower yield. This is exactly the opposite of what would be expected. Perhaps it could have a social interpretation that might be related to conservatism. In many cases conservatism implies the irrational resistance to innovation which may be caused by uncertainties (Cannarella and Piccioni, 2010). Producers with many years of experience may have got used to their routines, simplified and standardized processes, and therefore might be more resistant to change. At the other hand, producers with little years of experience might still be in the phase of experimentation and therefore adapt better to innovations that are proposed by the advisers. Consequently, the better adaptation to current innovations may be related to a higher yield.

As the sample size of producers was too small to do a statistical typology, it was not possible to adapt solutions for the different types of farms. Expected is that the duration of the cycle would divide the farms into different types. As many inputs almost automatically increase when the cycle length increases, this might have a blinding effect about the role of these inputs on yield. Decreasing the importance of the most important variable cycle length by dividing the farms into groups might result in more insights and therefore more possibilities for yield-gap closing.

4.6 Evaluation on the used methodology

Table 10. SWOT analysis for the used methodology.

Strengths	**Weaknesses**
• Close collaboration with producers. • In-depth understanding of the farming systems. • A representative sample was taken from the total amount of producers.	• Small sample size. • Sample size too small for making a typology. • Labour intensive method.
Opportunities	**Threats**
• Use of a bigger sample of at least 50 different producers in order to do a statistical typology (Hair et al., 2010).	• Producers ask many crop management related questions to the investigators. However it is intended to not give too many

• Reduce labour by adapting the way of measuring the phenology of the plants which was the most time-consuming activity and wherefore a high degree of detail was taken into account. • Use of tablets instead of notebooks by the investigators.	advices, it still might bias the results. • Few producers don't manage their notebook properly.

5. Conclusions

The average yield gap of greenhouse tomatoes in Uruguay was 48%. The yield-gaps were explained by cycle length, potassium fertigation and low relative humidity. In order to reduce yield-gaps, it is possible to improve management without increasing the production costs by for example better crop planning and fertilizer management. The sample size was rather small and the data showed considerable variability. With a larger sample size, a typology could be made and, hence, conclusions could be adapted to the different type of farms.

6. References

Alliaume, F.; Rossing, W.A.H.; García, M.; Giller, K.; Dogliotti, S. 2013. Changes in soil quality and plant available water capacity following systems re-design on commercial vegetable farms. European Journal of Agronomy 46: 10-19.

Alliaume, F; Rossing, W.A.H.; Tittonell, P.; Jorge, G; Dogliotti, S. 2014 Reduced tillage and cover crops improve water capture and reduce erosion of fine textured soils in raised bed tomato systems. Agriculture, Ecosystems & Environment 183: 127-137.

Besford, R.T. 1978. Effect of replacing nutrient potassium by sodium on uptake of and distribution of sodium in tomato plants. Plant and Soil 50: 399–409

Bakker J. C. 1991a. Analysis of Humidity Effects on Growth and Production of Glasshouse Fruit Vegetables. Thesis, Agricultural University, Wageningen**.**

Bakker J. C. 1991b. Leaf conductance of four glasshouse vegetable crops as affected by air humidity. Agric. Forest Meteor 55: 23–36.

Cannarella, C.; Piccioni, V. 2010. " Do the right thing" : Innovation diffusion and risk dimensions in the passage from conventional to organic agriculture. Journal of Central Europian Agriculture 11 (1): 113-129.

Castilla, N. 1995. Manejo del tomate en cultivo intensivo con suelo. Nuez,F. (ed.) El cultivo del Tomate. Ediciones Mundi-Prensa, Madrid: 189-225.

Castilla, N. 2013. Irrigation and fertilization. Greenhouse technology and management (2): 197-203. Online available at: http://www.cabi.org.ezproxy.library.wur.nl/cabdirect/FullTextPDF/2012/20123415774.pdf

Centraal Bureau voor de Statistiek (CBS), 2013. Statistisch jaarboek 2013, 14.11 Tomaten, oogst en teeltoppervlakte, 1947-2012: 151.

Coltman, R.R.; Riede, S.A. 1992. Monitoring the Potassium Status of Greenhouse Tomatoes Using Quick Petiole Sap Tests. HortScience 27 (4): 361-364.

DIEA/DIGEGRA, 2013. Encuestas hortícolas 2013: Zonas Sur y Litoral Norte. Serie de encuestas Nº 318. Marzo 2014.

DIEA, 2013. Recuentos preliminaries del Censo Agropecuario 2011. Online available at: http://www.mgap.gub.uy/portal/hgxpp001.aspx?7,5,694,O,S,0,MNU;E;55;9;MNU;E;55;9;MNU;

DINAMA/MGAP. 2005. Plan de Acción Nacional de Lucha contra la Desertificación y la Sequía.

Dogliotti, S.; García, M.C; Peluffo, S.; Dieste, J.P.; Pedemonte, A.J.; Bacigalupe, G.F.; Scarlato, M.; Alliaume, F.; Alvarez, J.; Chiappe, M.; Rossing,

W.A.H. 2013. Co-innovation of family farm systems: A systems approach to sustainable agriculture. Agricultural Systems 126: 76-86.

Dogliotti, S.; Abedala, C.; Aguerre, V.; Albín, A.; Alliaume, F.; Alvarez, J.; Bacigalupe, G.F.; Barreto, M.; Chiappe, M.; Corral, J.; Dieste, J.P.; García de Souza, M.C.; Guerra, S.; Leoni, C.; Malán, I.; Mancassola, V.; Pedemonte, A.; Peluffo, S.; Pombo, C.; Salvo, G.; Scarlato, M. 2012. Diseño, implementación y evaluación de sistemas de producción intensivos sostenibles en la zona sur del Uruguay. Serie FPTA nº 33.

Doré, T.; Clermont-Dauphin, C.; Crozat, Y.; David, C.; Jeuffroy, M.-H.; Loyce, C.; Makowski, D.; Malezieux, E.; Meynard, J.-M.; Valantin-Morison, M. 2008. Methodological progress in on-farm regional agronomic diagnosis. A review. Agronomy for Sustainable Development 28: 151-161.

Doré, T.; Sebillotte, M. and Meynard, J.M. 1997. A diagnostic method for assessing regional variations in crop yield. Agricultural Systems 54 (2): 169-188.

FAOSTAT, 2015. Countries delivering the 5 highest tomato yields 2000 – 2013. Webpage accessed on 6-11-2015.

Feller, C.; Bleiholder, H.; Buhr, L.; Hack, H.; Hess, M.; Klose, R.; Meier, U.; Stauss, R.; Van Den Boom, T.; Weber, E. 1995. Phänologische Entwicklungsstadien von Gemüsepflanzen: II. Fruchtgemüse und Hülsenfrüchte. Nachrichtenbl. Deut. Pflanzenschutzd. 47, 217-232. Accessible at http://www.bba.de/veroeff/bbch/bbcheng.pdf

Fermont, A. M.; van Asten, P.J.A.; Tittonell, P.; van Wijk, M.T.; Giller, K.E. 2009. Closing the cassava yield gap: An analysis from smallholder farms in East Africa. Field Crops Research 112: 24–36.

Fertiberia, S. A., 2005. Determinación, interpretación y consecuencias prácticas del análisis de suelo.

Garnett, T.; Appleby, M. C.; Balmford, A.; Bateman, I.J.; Benton, T.G.; Bloomer, P.; Burlingame, B.; Dawkins, M.; Dolan, L.; Fraser, D.; Herrero, M.;

Hoffmann, I.; Smith, P.; Thornton, P.K.; Toulmin, C.; Vermeulen, S.J.; Godfray H.C.J. 2013. Sustainable Intensification in Agriculture: Premises and Policies. Science 341: 33-34.

Hair, J. F.; Black, W.C.; Babin, B.J.; Anderson, R.E.; 2010. Multivariate Data Analysis: A Global Perspective, Seventh Edition, Pearson.

Hannachi, A.; Fellahi, Z.E.A.; Bouzerzour, H.; Boutekrabt, A. 2013. Correlation, Path Analysis and Stepwise Regression in Durum Wheat (Triticum Durum Desf.) under Rainfed Conditions. Journal of Agriculture and sustainability 3 (2): 122-131.

Hebbar, S.S.; Ramachandrappa, B.K.; Nanjappa, H.V.; Prabhakar, M. 2004. Studies on NPK drip fertigation in field grown tomato (Lycopersicon esculentum Mill.) European Journal of Agronomy 21(1): 117-127

HUANG, Y.; LI, Y.; WEN, X. 2011. The Effect of Relative Humidity on Pollen Vigor and Fruit Setting Rate of Greenhouse Tomato under High Temperature Condition. Acta Agriculturae Boreali-Occidentalis Sinica.

Just, R.E. 1975. Risk Aversion under Profit Maximization. American Journal of Agricultural Economics 57 (2): 347-352.

Kanai, S.; Moghaieb, R.E.; El-Shemy, H.A.; Panigrahi, R.; Mohapatra, P.K.; Ito, J.; Nguyen, N.T.; Saneoka, H.; Fujita, K. 2011. Potassium deficiency affects water status and photosynthetic rate of the vegetative sink in green house tomato prior to its effects on source activity. Plant Science 180 (2): 368-374

Lin, Y-H. 2010. Effects of potassium behaviour in soils on crop absorption. African Journal of Biotechnology 9 (30): 4638-4643.

Lobell, D.B.; Cassman, K.G.; Field, C.B. 2009. Crop Yield Gaps: Their Importance, Magnitudes, and Causes. Annual Review of Environment and Resources. 34: 179-204.

Matson, P. A.; Parton, W. J.; Power, A.G.; Swift, M.. 1997. Agricultural intensification and ecosystem properties. Science 277:504–509.

Molina, E.; Salas, R.; Castro, A. 1993. Curva de crecimiento y absorción de nutrimentos en fresa (Fragaria x ananasa cv. Chandler) en Alajuela. Agronomía Costarricense 17 (1): 67 - 73.

Peet, M.M. 2005. Tomatoes: Irrigation and Fertilization. Department of Horticultural Science, North Carolina State University, USA.

Reiners, S.; Petzoldt, C.H.; Hoffmann, M.P.; Schoenfeld, C.C. 1999. Integrated Crop and Pest Management Recommendations for Commercial Vegetable Production. Cornell Cooperative Extension, Ithaca, New York.

Schwarz, D.; Thompson, A.J.; Kläring, H.P. 2014. Guidelines to use tomato in experiments with a controlled environment. Frontiers in Plant Science 5: 625.

Van Ittersum, M.K.; Cassman, K.G.; Grassini, P.; Wolf, J.; Tittonel, P.; Hochman, Z. 2013. Yield gap analysis with local to global relevance - A review. Field Crops Research 143: 4-7.

Van Ittersum, R.; Rabbinge, M.K. 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Research 52: 197-208.