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An investment order tool to guide development of greenhouse horticulture for two specific regions

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Abstract

Growers worldwide often lack means to find the economically soundest order of investing. Authorities face similar problems when deciding which developments to stimulate. For Dutch greenhouse horticulture, models for production, climate, revenue and costs, allow selection of an optimal investment order. This approach was widened into “Adaptive Greenhouse Methodology” which allows evaluation of worldwide climate and greenhouse technology combinations. However, running the models requires expert skills. Our goal was to deliver a simplified software tool, which would allow horticultural suppliers, researchers and growers to autonomously rank alternative investments, for a specific combination of region, greenhouse design and crop. The Investment Order Tool was developed in cooperation with selected horticultural supply companies for the regions Almeria in Spain and the Jordan Valley. In Spain, a flat roofed Parral type greenhouse was compared to an industrial multi-span greenhouse. In Jordan a single tunnel greenhouse was compared to an industrial multi-span greenhouse with passive crop based cooling. The Investment Order Tool uses a one-time run of the Adaptive Greenhouse Methodology based on local information. This data set allows further off-line calculations. All adaptations in greenhouse construction and cultivation system are defined as relative production changes from the local standard. The adaptations are provided with their specific costs and benefits. The investments compared include: reverse osmosis; substrates; nutrient dosing; climate-adapted cultivars; recirculation of drainage water; ventilation capacity; shading screens and thermal screens. The Investment Order Tool informed growers on the investment order with the highest return on investment and the investment order with the lowest demand for capital. Nursery specificity was realized by permitting user defined yield and market price level per month and by defining a first and second class for product quality. It is hoped the Investment Order Tool encourages growers and local authorities to base investment decisions on increasingly solid knowledge.

Keywords: economics, decision support, cultivation system, greenhouse type, Mediterranean

INTRODUCTION

The Wageningen University & Research, Greenhouse Horticulture unit did studies on greenhouse design and greenhouse technology level in a range of regions, including Ethiopia, Algeria and Kenya (Bakker, 2009; Van Os et al., 2009, 2017; Ketter et al., 2015). For many studies, different models were used to calculate the maximum possible yield given the climatic and greenhouse technical possibilities (Speetjens et al., 2012; De Zwart, 1996). This approach evolved into the adaptive greenhouse methodology (Vanthoor, 2011; Vanthoor et al., 2011) which combines three validated mathematical models: a) KASPRO; b) a crop growth model to simulate dry matter production; c) an economic model, to evaluate the profits. This methodology has been used for among other regions, Mexico (Elings et al., 2013), Taiwan (Hemming et al., 2014) and Turkey (Tuzel et al., 2017). A drawback of the use of these models is the need to run the programs off-line by experts and away from the actual regions.

Horticultural supply companies working in different regions expressed interest to use an off-line version of the adaptive greenhouse methodology for specific regions. The

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horticultural supply companies experienced that decisions on increasingly large investments were seemingly made in informal discussions rather than supported by a structured ranking of various investment alternatives. For the individual supply companies, the problem was not only supplying data but also demonstrating the trustworthiness of the data. With a group of supply companies it was decided to try and develop a simplified software tool to allow horticultural suppliers, researchers and growers to autonomously rank alternative investments in a particular region, for a specific greenhouse design and a given crop.

The goal was to develop an off-line software tool for two specific different regions which would allow stand-alone use in the field and which would give data that would support local growers in choosing an investment order.

MATERIALS AND METHODS

The regions of choice had to be established concentration areas of plastic house horticulture with an evolving technological level as opposed to areas of disruptive development (turnkey projects). Using these criteria, Almeria in Spain and the Jordan Valley in Jordan were selected. Within these regions, scenarios were developed for two greenhouse types, the most traditional type and a simple multi-span type. The multi-span was included because it allows for a wider range of climate related investments whereas the traditional types can be upgraded only to the point on which it becomes cheaper to convert to a multi-span.

The area of plastic houses in Almeria is about 30,000 ha (García-García et al., 2016). Our estimate is that there are about 40% of low-tech Parral type greenhouses (Figure 1); 36% improved Parral and 20% of maxed out Parral. The remaining area is about 4% of widely differing multi-spans and less than 1% of glasshouses. The plastic house technology ranges in detail, partly as a function of the huge variation in topographic and climatic diversity on microscale (García-García et al., 2016).

Figure 1. Basic Parral type greenhouse (Almeria).

The basic Parral is a construction of wooden poles of which only a part is anchored in the ground while other poles provide only downward vertical support (Figure 1). The poles carry a double layer of coarse wire mesh (40×40 cm) which holds a layer of plastic in between. The roof is flat. Advantages are the very low price, good behavior against strong winds common in this region, ease of construction for growers and three-dimensional flexibility to deal with slopes, ridges and land pieces of uneven shape. The basic Parral is low (1-2.5 m), without top ventilation, with perforated plastic that lets rainfall inside. The internal climate in any season includes periods of too hot, too cold and too humid conditions. The roof is whitewashed except in the winter. The transmissivity of the roof is low as the plastic easily loads with dust and deteriorates over a period of 3-4 years. The crop is grown in the soil, usually as an Almerian system called enarenado; a layer of 30 cm coarse sand on top of the original soil to which a layer organic manure is added.

The area of plastic houses in Jordan is about 3500 ha of which 3000 ha are in the Valley and 500 ha are spread in the Highlands. Over 90% of the greenhouse area consists of single

span tunnels, both low and high tunnels, covered with polyethylene (JDoS, 2018; Figure 2). The remaining area consists of widely differing multi-spans. The tunnels are usually 8 m wide and 53 m long. The supporting metal arches are founded in concrete sockets cast in the ground. Advantages are the very low price and easy construction. The ventilation is mainly created by opening the back and front with <5% top opening. The internal climate in any season includes too high and too low temperatures and periods of too high humidity. The roof is either whitewashed or mud covered except in the winter. The transmissivity of the roof is low as the plastic easily loads with dust and deteriorates over a period of 3-4 years. The crop is grown in the soil.

Figure 2. Basic tunnel greenhouse (Jordan).

For both areas, a basic multi-tunnel consists of span height 3 m, roof height 4.5 m, gutters for rainwater, fixed 0. Twenty-five $\text{m}^2 \text{m}^{-2}$ window opening and automated side ventilation $0.10 \text{ m}^2 \text{m}^{-2}$ (for a 10 bay greenhouse).

The Investment Order Tool is based on static data sets created by existing models (Figure 3). KASPRO couples physics of mass and energy transport in the greenhouse with modules that simulate various climate control equipment (De Zwart, 1996). The present KASPRO modules include a tomato crop growth model (Goudriaan and Van Laar, 1994) and an economic module as realized by Vanthoor (2011).

Figure 3. Relation between the complex and fully dynamic existing WUR-GH tools KASPRO and Economic Model with the simple static and stand-alone Investment Order Tool.

To get a static data set from the existing models, a full set of local climatic data must be loaded into KASPRO as well as parameters for the greenhouse structure used. For Almeria climate data were gathered from literature (García-García et al., 2016). For the Jordan Valley, a 2015 data set from a meteorological station from NCARE in Deir Alla was used. For the Jordan Highlands, data were retrieved from Amman airport for 2012 (Baeza-Romero et al., 2020). The technical description of the Almerian Parral, the Jordanian single spans and the multi-spans were found in reports (García-García et al., 2016; Blok et al., 2017; De Groot et al., 2018). The Economic model was reduced to the information needed for the regions studied. For the Investment Order Tool technical improvements were made operational by assigning to each investment a percentage of yield increase. These percentages were themselves output of dedicated runs with KASPRO.

To avoid adding investment effects up to unrealistically high yield levels, the percentage increase was made to diminish toward a maximum yield level for each system. The maximum yield levels were based on prior KASPRO runs. Some particular choices as made with the Investment Order Tool include: a) the assumption that growers invest their own capital and depreciation and maintenance cost are subtracted each year after an investment; b) the inclusion of logical presuppositions, e.g., recirculation presupposes the choice for substrate growing. The technology chosen including implicit choices is shown in the tool in an overview. Preferably, technology mentioned in the overview should be selected. If not, investments and yields will be lower; c) the yield level at which an investment becomes feasible is calculated and put in an overview table to allow users to consider when in the future, not yet feasible investments might become feasible.

Functionality was added to the Investment Order Tool by creating a user interface. The interface allows the user to add nursery specific information. The user information helps to change the reference level from a generic basic cultivation system and average regional prices into a nursery specific reference. This not only takes into account investments already done and yield levels for two quality classes but also actual price levels of the grower. The price levels are relevant for growers with specific better market deals for export or specialties and the amount of second-class fruits allows the Investment Order Tool to appreciate skill and/or special varieties. The user is then allowed to choose investments from a list of pre-selected feasible investments as well as the order in which they are applied. The Investment Order Tool subsequently calculates the profitability of the grower choices as well as the most profitable OR the lowest investment order, with investments every three years. Results are presented in graphs and tables.

RESULTS

The Investment Order Tool was tested by interviewing growers in the Almeria region as well as demonstrating the Investment Order Tool for a local bank and a local research institute (Table 1).

Table 1. Examples of yield assigned to various scenarios and various investment levels.

Scenario	Greenhouse type	Max yield level (kg m ⁻²)	Investment
Almeria	Parral	9.9	None
Almeria	Parral	16.1	Shade screen
Almeria	Multi-span	14.8	None
Almeria	Multi-span	23.2	Shade screen
Jordan Valley	Multi-span	23.5	None
Jordan Valley	Multi-span	30.5	Shade screen

In Figures 4-6, the Investment Order Tool is used to investigate the situation of a grower with an Almeria Parral with a winter variety. The model starts by asking basic information for the water quality and irrigation system (Figure 4). The fresh water salinity is used to assess the yield improvement after investment in a rainwater basin or a reverse osmosis installation. The yield drop caused by specific ECs for specific crops is based on literature (Sonneveld and

Van der Burg, 1991). The frequency of irrigation is used to determine the benefit of migrating from soil to substrate cultivation. Yields are allowed to increase 15% when the number of irrigation cycles increases from one to ten per day (Xu et al., 2004). The model also allows to evaluate the possible effects of undesirable ammonium contents of specific fertilisers to avoid related pH risks (Dickson et al., 2016). After the basic information, the user can define a basic scenario, in this case cherry tomato in Almeria in a multi-span greenhouse. The grower is then allowed to customize the reference situation by adding those investments, which were already present (Figure 4, middle). In a next step, nursery yield and selling price for first and second-class products are shown and may be changed on a per month basis (Figure 4, right). Higher selling prices or higher yields both increase the net benefit of the reference situation and thus more technologies may become feasible (and appear in screen). The introduction of customized economic data creates a new temporary data set with a new nursery specific reference.

basic information
Determine the basic parameters that apply to your situation.

Fresh water salinity (dS/m): (range: <1.1 to 2.5)

Irrigation frequency (cycle(s)/day): (range: 1 to 3)

☐ include Ammonium fertilizer comparison

Validate

Reference design definition
Determine your reference scenario:
1) Choose a basic scenario.
2) Select the technologies that you own.

Cherry-Almeria-Multitunnel

☐ Reverse osmosis ☐ Boiler 100W (thermal screen)

☐ Rain water ☒ Winter variety

☐ Substrate (quality water) ☐ Cooling by mist

☐ Recirculation (substrate)

☐ CO2

☐ Diffuse screen (no whitewash)

☐ Thermal screen

Validate

Yield customisation
Check the yield and turnover of the reference. Customize if necessary.

	Customized yield		Customized price	
	Yield (kg/m2)	selling price (€/kg)	Yield (kg/m2)	selling price (€/kg)
	1st class	2nd class	1st class	2nd class
calculate yearly values:	11.76	0.65	1.25	0.93
January	0.48	0.02	1.85	1.81
February	0.27	0.01	1.9	1.31
March	0.65	0.03	1.51	1.19
April	1.4	0.07	1.22	1.08
May	3.79	0.21	0.36	0.16
June	0.48	0.02	0.49	0.32
July	0	0	0.9	0.67
August	0	0	0	0
September	0	0	1.38	0.89
October	1.03	0.05	1.41	1.02
November	2.27	0.12	1.3	0.7
December	1.35	0.07	1.42	1.07

start

Figure 4. Consecutive basic input windows for salinity, irrigation frequency and ammonium fertiliser evaluation (left); Choice of reference scenario, in this case Tomato-Almeria-Parral and input of grower investments in this scenario (middle); Definition of yield level and price level for two fruit quality classes per month (right).

The grower is consequently allowed to fill three investment alternatives by typing in the year of investment. His first choice was investing a diffuse screen (year 1), adding cooling by mist (year 3) and collection of rain water (year 5). The second choice was cooling by mist (year 1), collection of rain water (year 3) and adding a diffuse screen (year 5). The third choice was collection of rain water (year 1), a diffuse screen (year 3) and cooling by mist (year 5). Based on the nursery specific reference, the Investment Order Tool now calculates a “least investment” order in which the feasible technologies are selected in order of increasing depreciation cost with an investment every 3 years (Figure 5). The Investment Order Tool also calculates a “preferred” order by investing every 3 years in the technology with the highest net benefit (Figure 5). The cumulative benefits of the “least investment” order, the “preferred” order and the user orders 1, 2 and 3 are then shown in a graph (Figure 5).

In this case, user order 1 is slightly more profitable than the “preferred” order (which is investing every 3 years in the technology with the highest net benefit) because the investment interval in user order 1 was 2 instead of three years. The investment in rain water collection proved to be marginally profitable (about as much costs as profits). But the investment in a diffuse screen was the most feasible investment.

For advisors and authorities the values used to calculate the net benefit of each technology are available in a summary table (Figure 6). The balance of the data reference, user reference and each technology are shown. Values are calculated relative to the user reference.

Figure 5. Graphic representation of the cumulative benefit generated by different investment orders.

Summary of the economic balance:		Individual balance of the different alternatives									
Cherry tomato - Almeria - Multitunnel - Ref Surface: 1ha		Dataset Reference	User Reference	Reverse osmosis	Rain water	CO ₂	Diffuse screen (no whitewash)	Thermal screen	Boiler 100W (thermal screen)	Winter variety	Cooling by mist
Turnover	€/year/m ²	12.1	12.4	12.4	12.4	12.0	14.3	12.2	22.9		13.3
Yield	kg/year/m ²	13.0	12.3	12.3	12.3	12.6	16.1	12.4	19.3		13.7
Variable cost	€/year/m ²	3.9	4.0	4.1	3.9	7.0	4.2	4.0	24.5		4.1
Depreciation	€/year/m ²	2.9	2.9	3.2	3.0	2.9	4.0	4.2	5.0		3.4
Netto - benefit	€/year/m ²	5.3	5.6	5.1	5.6	2.0	6.1	4.0	-6.7		5.8
Investement	€/m ²	28.6	28.6	2.9	1.5	1.0	5.5	6.5	18.9		5.0
Investement Space	€/year/m ²				0.0		0.5				0.2

Figure 6. Part of the economic summary of the result of different investments for the given scenario of Cherry tomato in a multi tunnel in Almeria, Spain.

DISCUSSION

The Investment Order Tool was flexible enough to have meaningful discussions with growers. Growers with special varieties, with export contracts and with organic products enjoy special prices, which allows them investments that are more diverse. Most growers have a rough appreciation of the investments that could be feasible, but the perception of risks easily prevents them from acting on the best choices. As an example, organic growers perceive the risks of high humidity as cause of fungal diseases as so important they sometimes avoid thermal screens even though the resulting lower plant head temperatures in clear nights are a much worse cause of fungal disease by invoking condensation (as discussed by Montero et al., 2013). Another outcome was that the appreciation of light as a driver of yield is often underestimated. This is reflected by the preference of white wash with a heavy shading factor, even though screening has become more feasible. Some growers apply whitewash 4-5 times per season accepting the lower cost and higher yield presented by a light screen (as discussed by García-Balaguer et al., 2017). The irrigation equipment is generally effective, but recirculation of drainage water is almost absent in the region. With 30000 ha involved, this situation deserves a structural approach in cooperation with authorities.

In Jordan the economic situation in 2017-2018 as influenced by war in neighboring countries, was so bad the Investment Order Tool showed no investments were feasible at the then current market prices. Investments by export-oriented nurseries quickly concentrated on passively cooled greenhouses i.e., cooling by the evaporating plants rather than by using the water-consuming pad and fan technology. This requires plastic houses with very large

ventilation openings and ample height to stimulate natural ventilation by air movement (Short and Lee, 2002). For the growers involved, this already required large technological steps including: a) harvesting on trolleys; b) using high wire spool systems; c) using substrate and drip irrigation. A change not yet incorporated in the Investment Order Tool was the change in the propagation system from a small plant in a plug to larger plants in larger plugs or in a plug-block combination. In Jordan investing in recirculation of nutrient solution in the same cultivation is not yet feasible even though Jordan is one of the four most water stressed countries in the world (Fileccia et al., 2015). The alternative is to reuse drain water in an adjacent lower value crop, usually a soil born crop.

Some other outcomes in general terms: a) the reverse osmosis proved straightforward information on the raw water EC maximum above which reverse osmosis is feasible; b) the switch to substrate was equally straightforward, with the exception for soils that allow 5 or more irrigation cycles per day; c) the climate-adapted varieties of the region proved indeed feasible in a winter cultivation in unheated greenhouses compared to the varieties developed for heated greenhouses; d) the recirculation of drainage water increased the costs more than or equal to the increase in yield; e) the investments in ventilation capacity, shading screens and/or thermal screens proved always interesting although the exact combination depends on microclimate information (as discussed by Baeza et al., 2005; Baptista et al., 2012). Finally heating and carbon dioxide were not yet within reach of most Parral and the basic multi-span. In all cases, the outcome is dependent on many variables like cultivation period and length, microclimate and price agreements, etc., which illustrates the need for a tool like the Investment Order Tool.

CONCLUSIONS

The Investment Order Tool calculates the cumulative profit realized following different investment strategies in a given context. The Investment Order Tool helps growers to better discuss the best investments and to avoid not (yet) profitable investments based on local climate, local yield and local price levels. Advisors can use the Investment Order Tool to optimize an investment strategy based on available grower skills. Authorities can use the Investment Order Tool to find almost feasible investments that qualify for regional stimulation. The Investment Order Tool can also be used to find knowledge gaps in specific regions, which can guide actions, by extension, research and educational organisations.

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Literature cited

- Baeza, E.J., Pérez-Parra, J., and Montero, J.I. (2005). Effect of ventilator size on natural ventilation in parral greenhouse by means of CFD simulations. International symposium on greenhouse cooling: methods, technologies and plant response. *Acta Hortic.* 691, 465–472 <https://doi.org/10.17660/ActaHortic.2005.691.56>.
- Baeza Romero, E.J., van Os, E.A., van der Salm, C., Tsafaras, I., and Blok, C (2020). Exploring the boundaries of the passive greenhouse in Jordan: a modelling approach. *Acta Hortic.* 1268, 43-50. <https://doi.org/10.17660/Actahortic.2020.1268.6>.
- Bakker, J.C. (2009). Energy saving greenhouses. *Chron. Hortic.* 49, (3), 14.
- Baptista, F., Bailey, B.J., and Meneses, J.F. (2012). Effect of nocturnal ventilation on the occurrence of *Botrytis cinerea* in Mediterranean unheated tomato greenhouses. *Crop Prot.* 32, 144–149 <https://doi.org/10.1016/j.cropro.2011.11.005>.
- Blok, C., Van Os, E.A., Daoud, R., Waked, L., and Hasan, A. (2017). Hydroponic Green Farming Initiative. GTB1447 (Wageningen, The Netherlands: Wageningen University & Research), <http://edepot.wur.nl/426168>.
- De Groot, N., Haddadin, W. and Schurink, E. (2018). Horticulture in Jordan, A sector in danger? Report

commissioned by the Embassy of the Kingdom of the Netherlands in Jordan.

De Zwart, H.F. (1996). Analysing energy-saving options in greenhouse cultivation using a simulation model. Ph.D. thesis (Wageningen, The Netherlands: Agricultural University).

Dickson, R.W., Fisher, P.R., Argo, W.R., Jacques, D.J., Sartain, J.B., Trenholm, L.E., and Yeager, T.H. (2016). Solution ammonium: nitrate ratio and cation/anion uptake affect acidity or basicity with floriculture species in hydroponics. *Sci. Hortic. (Amsterdam)* 200, 36–44 <https://doi.org/10.1016/j.scienta.2015.12.034>.

Elings, A., Speetjens, S.L., and Garcia Victoria, N. (2013) Greenhouse designs for Mexico. Aguascalientes, Querétaro and Sinaloa. <http://edepot.wur.nl/302763>.

Fileccia, T., Hovhera, V., Punda, I., and Manzo, S. (2015) Jordan: Water along the food chain. <http://www.fao.org/3/a-i4608e.pdf>.

García-Balaguer, M.L., Sánchez-Guerrero, M.C., Medrano, E., Baeza, E.J., Sánchez-González, M.J., Porras, M.E., Giménez, M., and Lorenzo, P. (2017). Mobile shading versus whitewashing: evaluation of the agronomic response of a tomato crop. *Acta Hortic.* 1170, 959–966 <https://doi.org/10.17660/ActaHortic.2017.1170.123>.

García-García, M.C., Céspedes-López, A.J., Pérez Parra, J.J., and Lorenzo Mínguez, P. (2016). El Sistema de Producción Hortícola Protegido de la Provincia de Almería (Almería, Spain: IFAPA).

Goudriaan, J., and Van Laar, H.H. (1994). Modelling Potential Crop Growth Processes (Dordrecht, The Netherlands: Kluwer Academic Publishers), pp.238.

Hemming, S., Speetjens, S.L., Wang, D., and Tsay, J.R. (2014). Greenhouse design for vegetable production in subtropical climate in Taiwan. *Acta Hortic.* 1037, 65–74 <https://doi.org/10.17660/ActaHortic.2014.1037.4>.

JDoS. (2018). Jordan Department of Statistics. Agricultural Statistics 2015. <http://dosweb.dos.gov.jo/product-category/agricultural-statistics> (accessed December 14, 2018).

Ketter, N.C., Kariuki, W., Wesonga, J.M., Elings, A., and Hoogerwerf, F. (2015). Vegetative growth of rose flower in cocopeat and soil in Naivasha, Kenya. *Acta Hortic.* 1104, 95–102 <https://doi.org/10.17660/ActaHortic.2015.1104.15>.

Montero, J.I., Muñoz, P., Sánchez-Guerrero, M.C., Medrano, E., Piscia, D., and Lorenzo, P. (2013). Shading screens for the improvement of the night-time climate of unheated greenhouses. *Span. J. Agric. Res.* 11 (1), 32–46 <https://doi.org/10.5424/sjar/2013111-411-11>.

Short, T.H., and Lee, I.B. (2002). Temperature and airflow predictions for multi-span naturally ventilated greenhouse. *Acta Hortic.* 578, 141–152 <https://doi.org/10.17660/ActaHortic.2002.578.16>.

Sonneveld, C., and Van der Burg, A.M.M. (1991). Sodium chloride salinity in fruit vegetable crops in soilless culture. *Neth. J. Agric. Sci.* 39, 115–122.

Speetjens, B., Hemming, S., Wang, D., and Tsay, J.-R. (2012). Design of a vegetable greenhouse system for subtropical conditions in Taiwan. GTB 1189 (Wageningen, The Netherlands: Wageningen University & Research).

Tuzel, Y., de Zwart, H.F., Sapounas, A., Hemming, S., and Stanghellini, C. (2017). Improvement of greenhouse climate control in Mediterranean conditions: a case study from Turkey. *Acta Hortic.* 1170, 889–896 <https://doi.org/10.17660/ActaHortic.2017.1170.114>.

Van Os, E.A., Elings, A., and Voogt, W. (2009). The water balance in Ethiopian greenhouses. A case study for two rose farms. Report 281 (Wageningen, The Netherlands: Wageningen University & Research).

Van Os, E.A., Bruins, M.A., Ruijs, M.N.A., Sapounas, A., and Speetjens, B. (2017). Prospects of hydroponics and protected cultivation in semi-arid regions piloted in Algeria. *Acta Hortic.* 1176, 65–72 <https://doi.org/10.17660/ActaHortic.2017.1176.9>.

Vanthoor, B.H.E. (2011). A model-based greenhouse design method. Ph.D. thesis (Wageningen, The Netherlands: Wageningen University).

Vanthoor, B.H.E., Stanghellini, C., Van Henten, E.J., and De Visser, P.H.B. (2011). A methodology for model-based greenhouse design: Part 1, a greenhouse climate model for a broad range of designs and climates. *Biosyst. Eng.* 110 (4), 363–377 <https://doi.org/10.1016/j.biosystemseng.2011.06.001>.

Xu, G., Levkovitch, I., Soriano, S., Wallach, R., and Silber, A. (2004). Integrated effect of irrigation frequency and phosphorus level on lettuce: P uptake, root growth and yield. *Plant Soil* 263 (1), 297–309 <https://doi.org/10.1023/B:PLSO.0000047743.19391.42>.