Modelling the Amount of Materials to Improve Inventory Datasets of Greenhouse Infrastructures

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Abstract

Purpose: Previous studies have shown the importance of including agricultural capital goods in environmental assessments. In particular for protected crops, greenhouse structural components may account for nearly 30% of the total in environmental impact categories such as resource depletion and global warming. The lack of appropriate datasets can make it difficult to include these structural components. The present paper provides a modelling approach for the greenhouse inventory stage to provide better assessments of greenhouse production systems.

Methods: In this study, four main greenhouse structures were assessed: a glass greenhouse, a multi-tunnel greenhouse, a local Mediterranean type known as the *parral* greenhouse and a low-tunnel greenhouse. After selecting the main materials of the structure, we generated equations to calculate the amount of the main structural materials as a function of the main greenhouse dimensions. We performed a quality assessment of the data used for different greenhouse structures. We also calculated a simplified environmental assessment made by the different structures to the climate change category in order to test the effects of the different amounts of material in the four greenhouse types.

Results: Equations to calculate the amount of the main greenhouse materials as a function of greenhouse size are provided. For the four greenhouse types under consideration, statistical correlations showed a good fit between the amounts of greenhouse materials and the parameters related to the main greenhouse dimensions, such as greenhouse perimeter, surface and volume. The results from the complementary impact assessment study show that glass greenhouses contributed the most in the climate change category, with an average value of 2.9 kg CO_2 eq·m^{-2}. After variability was taken into account, multi-tunnel and *parral* greenhouses showed similar values of between 0.6 to 1.2 kg CO_2 eq·m^{-2}, while low-tunnel greenhouses had the lowest ranges, between 0.45 and 0.53 kg CO_2 eq·m^{-2}. The environmental assessment was done using the square metre as a reference flow, so the actual impact depends on the functional unit selected, which is usually the yield.

Conclusions: Application of the equations developed in this study provides an easy way to calculate the quantity of materials used to make greenhouses of different dimensions, thus resulting in more accurate calculation of greenhouse production system impacts. This analysis also highlights the importance of the different amounts of materials used to build these structures and, therefore, the need to include ranges of uncertainty in environmental analyses.

Keywords: glasshouse, multi-tunnel greenhouse, low-tunnel greenhouse, parral greenhouse

1. Introduction

In accordance with ISO standards 14040 (ISO 2006a) and 14044 (ISO 2006b), in order to be accurate when assessing the environmental impact of products, infrastructure must be taken into account, as capital goods are explicitly part of the production system. Several authors (Frischknetcht et al., 2007; Nemecek et al., 2003) also confirm the need to include capital goods in agricultural assessments. Most guides recommend including capital goods in the assessment when they contribute more than 5% of the total (EU-JRC-IES, 2010; ISO-14067, 2011). In particular for greenhouse crop production, previous studies have shown that, in environmental impact categories such as resource depletion, global warming and cumulative energy demand, the structure (including the framework, cladding materials and non-structural accessories) accounts for nearly 30% of the total (Antón, 2004; Martínez-Blanco et al., 2011 ; Russo and Scarascia-Mugnozza, 2005; Torrellas et al., 2012c).

Although protected crops make an important contribution to plant production, no official statistics are available on the total greenhouse area at the world level. Some sources (Kacira, 2011) estimate a total world greenhouse area of close to 3 million ha for all greenhouse types, mostly located in Asia. European statistics show that 198,500 ha of crops are grown under protected conditions, with 80% located in Mediterranean countries (Eurostat, 2008). The main structures in northern European countries are glass greenhouses, but there is a very limited number of these structures in warmer countries, where commercial multi-tunnel greenhouses and local structures such as *parral* greenhouses (steel or wooden frame structures) are the most common (EFSA-PPR, 2009).

Data collection in a life cycle assessment (LCA) is a laborious undertaking. Nemecek (2005) therefore suggests that the selection of representative life cycle inventory data should be based on a modelling approach or a single-data-source approach. In this second approach, a representative source can be used, such as a pilot farm or an experimental field. Most studies carried out to date have been done following the second approach on a specific greenhouse structure (e.g. Antón et al., 2005; Boulard et al., 2011; Martínez-Blanco et al., 2011; Romero-Gómez et al., 2009; Torrellas et al., 2012a).

However, in greenhouse production and structures, there is great variability in the kinds of materials used (glass cover, plastic cover, etc.), as well as greenhouse geometry (single span, multi-span, arched roof, flat roof, etc.). Moreover, greenhouse size or the factor of scale varies a great deal, depending on the features of the geographic area. This factor of scale indicates that the larger the covered area, the lower the amount of materials per area and therefore the lower the environmental load per area and production unit. Consequently, given the significance of the contribution of infrastructure and the difficulty of defining a “representative” greenhouse as a single-data source, a modelling approach could be a more comprehensive way to assess the amount of materials used in greenhouse structures.

The main goal of this paper is therefore to use a modelling approach to provide inventory datasets for different greenhouse structures. With this aim in mind, we generated equations to calculate the amount of the main structural materials as a function of the main greenhouse dimensions and performed a statistical assessment of the data for different greenhouse structures. We also calculated a simplified environmental assessment for the climate change category in order to test the effects of the different amounts of material in the four greenhouse types.

2. Methods

2.1 Greenhouse Structures

In this study, four main greenhouse structures were assessed: a glass greenhouse, a multi-tunnel greenhouse, a *parral* greenhouse and a low-tunnel greenhouse (Figure 1). Glass greenhouses are common in temperate and cold climates. Multi-tunnel greenhouses are commercial growing structures covered with plastic that are used in regions with warm and mild winter climates. *Parral* greenhouses are the most common greenhouse structures in southern Spain, the region with the most extensive production of protected crops in Europe. Finally, low-tunnel greenhouses are the most simple greenhouse structures and are common in most horticultural areas of the world.

(Figure 1)

2.1.1 Glass Greenhouse

The most common glass greenhouse structure is the commercial Venlo glass greenhouse; due to its popularity it is the only glass greenhouse type we considered in this study. The Venlo glass greenhouse has straight side walls and a roof formed by two slopes of equal pitch. The roof slope considered in our study was 22º. The frame structure is usually made of metal, steel and aluminium, and the covering material is glass. Steel elements include girders, roof bars, stability braces, rails, posts, tie beams, foundation reinforcements, vent opening mechanisms and a high-wire system to support crops. Aluminium elements include gutters, ridges, bars, vent-opening mechanisms and energy screens. The covering, front walls and side walls are made of uncoated flat glass. Concrete is used for the foundations and main path. Further details of the Venlo structure can be found in Bakker et al. (1995). Table 1 shows the average, minimum and maximum dimensions we considered for this kind of greenhouse. The minimum covered area was 512 m^2 and the maximum was 104,000 m^2; span widths ranged from 6 to 12.8 m and each span could have from 1 to 4 bays.

2.1.2 Multi-tunnel Greenhouse

This type of greenhouse is a commercial multispan structure with an arched roof and a steel frame (Castilla, 2004; Matallana and Montero, 1995). Span widths can range from 6 to 10 m.

Foundations consist of concrete footings under the steel frame. In this kind of greenhouse, the distance between the side wall posts is usually 2.5 m and the distance between the inside posts is 5 m. The roof is made up of a number of steel hoops at a distance of 2.5 m from each other. There can be one or two roof vents in each span. All the vents are usually covered with an insect-proof screen. Steel elements include posts, frame reinforcements, gutters, braces, vents and hoops.

The roof covering, front walls and side walls are made of polyethylene, usually in the form of a coextruded three-layer plastic film for the roof and polycarbonate sheets or plastic film for the walls. For the multi-tunnel greenhouse, the minimum covered area was 432 m^2 and the maximum was 62,500 m^2 (Table 1).

2.1.3 *Parral* Greenhouse

A *parral* greenhouse is a simple steel or wooden frame structure with a flexible plastic cover. The main parts of the *parral* greenhouse structure include a vertical structure consisting mainly of a number of rigid wooden or steel posts that can be located around the perimeter or inside the greenhouse with foundations consisting of concrete footings supporting the steel frame.

The roof is based on a traditional square steel-wire frame. It is a flexible horizontal structure made of a single wire or corded wires that carry the force of wind uplift to the ground or provide support for the plastic mesh cover (Pérez-Parra, 1998). The covering material is usually multiple layers of ethylene-vinyl acetate (EVA) and low-density polyethylene (LDPE) film.

Natural ventilation is provided through roof openings in each span and two side wall openings. All the openings are covered with insect-proof screens. For the *parral* greenhouse, the minimum covered area considered in this study was 432 m^2 and the maximum was 22,500 m^2 (Table 1).

2.1.4 Low-tunnel Greenhouse

Low-tunnel greenhouses are temporary unheated structures. They are very popular for growing strawberries and small food crops. They have a single span that can be 0.3 to 3 m high and 0.8 to 9 m wide. The span is created with hoops made of steel or plastic tubes, usually polyethylene (PE) or polyvinylchloride (PVC), covered with plastic film. For the low- tunnel greenhouse, the minimum covered area used in this study was 24 m^2 and the maximum was 900 m^2 (Table 1).

2.2 Inventory Based on the Modelling Approach

The amount of materials for each of the 35 samples for the four scenarios was calculated in accordance with the greenhouse dimensions and frame structures. The dimensions of the different scenarios were selected based on our own experience of the most representative real scenarios, as well as known references (Castilla, 2004; Bakker et al., 1995; Perez Parra, 1998; Matallana and Montero, 1995) and personal contacts with greenhouse manufacturers.

Following the recommendations of the ILCD (EU-JRC-IES, 2010), we selected the main materials of the structure that had contributed more than 5% to the global environmental assessment in a previous study (Torrellas et al., 2012b). We therefore developed equations to calculate the amount of the main greenhouse materials as a function of greenhouse size (Table 1). The equations were developed by using the dimensions of 35 different real greenhouses, calculating the amount of materials needed for each size and establishing statistical regressions between the greenhouse size variables (e.g. covered area, number of spans, perimeter and volume) and the amount of materials. For each material, the variables that produced the best fit were chosen.

(Table 1)

2.3 Data Quality

Data quality must be estimated in accordance with ISO 14044 (2006) quality criteria. We followed the guidelines of the ILCD data quality indicators, which allowed us to classify the achieved data quality of the LCI datasets in terms of their technological representativeness (TeR), geographical representativeness, (GR), time-related representativeness (TiR), completeness (C), methodological appropriateness (M) and precision (P). We complemented each factor with the criteria of the ecoinvent pedigree matrix (Weidema et al., 2012).

The precision quality indicator was expressed as a measure of the variability of data values for each piece of data expressed (e.g. low variance = high precision). Table 2 shows the quality rating and level for this indicator expressed as a function of the relative standard deviation of the sample.

(Table 2)

Overall data quality was calculated by summing up the achieved quality rating for each of the quality components. The rating of the weakest quality level, X_w, was counted 4 times. The sum was divided by the number of applicable quality components (i) plus 4 (equation 1).

$$DQR = \frac{TeR+GR+TiR+C+P+M+X_w \cdot 4}{i+4}$$ Equation 1

The data quality rating (DQR) result was used to identify the corresponding quality level. Three levels of data quality are identified in the ILCD guidelines: “high quality”, where the data quality level, DQL, is < 1.6; “basic quality”, where the DQL is > 1.6 and < 3; and “data estimate”, where the DQL is > 3 and < 4). Among other factors, the DQR covers quantitative criteria for accuracy, completeness and precision (EU-JRC-IES, 2012).

2.4 Climate Change Contribution

As mentioned above, the main goal of this paper is to provide inventory datasets for further greenhouse crop production life cycle assessments. However, as an example of the effect of the different amount of materials, contributions made by the different structures to the climate change category were calculated with their respective variability. The materials required to occupy one square metre for one year were selected as a reference flow. System boundaries included inputs and outputs in the manufacture of greenhouse components. Material disposal needs to be considered for recycling processes. Therefore, following the cut-off allocation procedure of Ekvall and Tilman (1997), these processes were out of the scope of the assessment. However, recycled metal was considered to be used to produce the metal parts in the four scenarios.

The midpoint indicator methodology was applied following IPCC Guidelines (IPCC, 2006). The life span of the metal parts in the structure was the same as the useful life of the greenhouse, which, in accordance with the European code (CEN, 2001), was 15 years for the glasshouse and the multi-tunnel greenhouse and 10 years for the low-tunnel greenhouse. The *parral* type is not included in the European code, since it is a locally made greenhouse structure. Its life span used for this greenhouse was 15 years, which is in accordance with local experience and also provides for direct comparison with the glasshouse and multi-tunnel greenhouse structures. The useful life of plastic was 3 years for film and 10 years for semi-rigid sheets (Montero et al., 2011)

3. Results

This section contains the equations generated to create the best fit for each of the main materials related to known and easy measurable dimensions such as covered area (S), perimeter (P), volume (V), number spans (N) and so on. This was calculated for each kind of structure (glass greenhouse, multi-tunnel greenhouse, *parral* greenhouse and low-tunnel greenhouse) while seeking the best correlation coefficient between experimental and modelled data. Tables 3, 4, 5 and 6 show the equations with the best fit between variables and correlation coefficients. Most amounts of material followed a potential function, which resulted in a considerable variation in the amount of materials for marginal changes in small greenhouse dimensions and minor variations in larger greenhouses. There was a linear correlation between some materials (i.e. coating and metals), while others, such as plastic roof covers, correlated directly to the ratio between the developed surface (S_d) and covered area (S). Finally, some materials showed constant values per square metre, such as aluminium in glass greenhouses and soil covering plastic in low-tunnel greenhouses.

3.1 Glass Greenhouse

For the glass greenhouse, the relevant materials were steel and aluminium for the frame, concrete for the foundations and glass. To simplify, the best fit found for steel (posts and stability braces) and concrete was based on the perimeter structure. It was difficult to find simple dimensions for the aluminium parts in the gutter, ridge and front and the glazing roof bars. We used a fixed value in this case and the respective coating. Glass was calculated as a function of the developed area. Steel coatings were also calculated as a function of the amount of the respective metal.

(Table 3)

3.2 Multi-tunnel Greenhouse

Two equations were used to calculate the amount of steel in the frame, depending on the number of roof vents. The first was used if there was one vent in each span, and the second if the number of vents was twice the number of spans.

The front side accounts for a major part of the total amount of steel in a multi-tunnel greenhouse. Therefore, the best dimension to include is the total greenhouse volume in relation to the number of spans. Like the glass greenhouse, the amount of concrete depends on the number of posts. The perimeter is therefore a good parameter to use to account for the total amount of concrete.

Two types of covers were studied, depending on the perimeter: plastic film and polycarbonate. The roof is usually covered with plastic film, a constant value. In addition, the plastic in the insect-proof screens was calculated as a function of greenhouse length, the number of spans and the number of vents. The steel coating was calculated as the area of steel to be covered. The steel frame had the worst fit, i.e. 0.82 for greenhouses with two vents per span and 0.84 for greenhouses with one vent per span (Table 4).

(Table 4)

3.3 *Parral* Greenhouse

For *parral* greenhouse structures, two materials were studied for the frame: wood and steel. The equations with the best fit to calculate the amount of steel or wood in the structure, the plastic cover and the foundations were obtained when the greenhouse surface area was used. The best fit for other steel parts, such as the ones used in the vents in the wooden greenhouses, the wire mesh and the gutters, was found by using the ratio of greenhouse volume to the number of spans. The zinc coating on the steel parts was calculated in terms of the total amount of steel. The structural part with the worst fit was the steel wire mesh (Table 5).

(Table 5)

3.4 Low-tunnel Greenhouse

This simple structure consists of a set of hoops and a plastic cover. The number of hoops depends on the length of the tunnel, the spacing between the hoops and span width, and the weight of the material used depends on number of hoops, as well as their diameter and thickness, while the amount of plastic depends on span width and tunnel height.

Equations were generated for the most common materials for the hoops: steel, high-density polyethylene (HDPE) and polyvinylchloride (PVC) (Table 6) as a function of the surface developed and diameter of the hoops, while the amount of plastic was a function of the developed surface. This can easily be calculated using the length of the arches and tunnels.

(Table 6)

3.5 Data Quality

Tables 7a and 7b show the statistical assessment: the average material value corresponding to one year per square metre, life span, geometric mean, variance of log transformed data, relative standard deviation (RSD) and the quality indicators of precision (P) and technological representativeness (TeR) for the different datasets used in the glass greenhouse, the multi-tunnel greenhouse, the *parral* greenhouse and low-tunnel greenhouse.

With the application of the methodology proposed by the ILCD complemented by the criteria of a pedigree matrix (Weidema et al 2012), it can be seen that the data quality of most of the components was basic, mainly due to sample variability. All the materials received very good scores in the completeness, time-related and geographical representativeness quality parameters, which are not shown in the tables.

Regarding completeness, all flows included were considered to be representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations.

Time-related representativeness (TiR). This means the degree to which the data set reflects the true population of interest regarding the time/age of the data. Updated data were used. We included the life span of the materials when calculating the time-related representativeness score. For example, for a life span of 15 years, materials that were less than 15 years old were given a score of 1.

Geographical representativeness (GR). The materials were given a score of 1 in this category; the selected data were representative of the geography in question.

Methodological appropriateness (M). Datasets were assessed by following the criteria described as Situation C2 “excluding interactions with other systems”, which means that the datasets did not include interactions outside the analysed system being documented. Therefore, all the materials received very good scores (1) in methodological appropriateness and consistency.

Technological representativeness (TeR). The selection of materials for the greenhouse structure was representative of the degree of technology in the greenhouse structure. Nevertheless, in this study we evaluated the adaptability of secondary data as criteria to determine TeR, which means that improving the database may also improve data quality. For instance, multilayer film is the most common plastic film for a multi-tunnel and *parral* greenhouse. We used LDPE plastic film as a secondary dataset, which therefore received a TeR score of 3. As this score depended on the dataset, we added the value for each component in Tables 7a and 7b.

In accordance with ILCD guidelines, precision is a “measure of the variability of the data values for each data expressed” and is scored based on the relative standard deviation. The results shown in Tables 7a and 7b indicate variability for the different materials as the relative standard deviation (RSD). The higher the RSD, the higher the P score. For instance, the concrete used in the glass greenhouse showed an RSD of 72.6 and thus a high P of 5. To be sure of the quality of the data, it is therefore important to be aware of the high variability of this component.

(Table 7a)

(Table 7b)

3.5 Climate Change Contribution

Figure 2 shows average emissions in the climate change impact category in kg CO_2 eq·m^{-2}·y^{-1} of the different kinds of structures and contribution of the different materials. The glass structure had considerable environmental impact (2.94 kg CO_2 eq·m^{-2}·y^{-1}) because of the high amount of glass and the high amount of steel to hold the glazing. Multi-tunnel structures showed average contributions of 0.97 and1.19 kg CO_2 eq·m^{-2}·y^{-1} depending on the number of vent openings. Average values for the *parral* greenhouse were slightly lower, 0.66 and 0.88 kg CO_2 eq·m^{-2}·y^{-1} depending on wooden or steel structure. Finally low-tunnels gave averages values between 0.45 and 0.53 kg CO_2 eq·m^{-2}·y^{-1} depending on the hoop material.

The main contributors in the glass greenhouse structure were glass (35.0%) and the metals in the frame, i.e. aluminium (27.2%) and steel (22.9%). For multi-tunnel greenhouses, the highest structural contributions were from the steel frame and ranged from 35% to 42.5%, depending on the different vent options and wall materials. The comparison of cover materials showed that the impact of the rigid plastic was six times higher than the plastic film's, i.e. a 22% increase when multi-tunnel greenhouses with rigid walls were compared with multi-tunnel greenhouses with plastic film walls.

In *parral* greenhouse structures, the mesh wire and plastic covering were the most important contributors, with similar percentages of nearly 22% each for steel-frame greenhouses and 30% each for wooden greenhouses. Regarding low-tunnel greenhouses, the main contributor was the plastic cover. When different frames were compared, steel arches showed the highest contribution and HDPE was the material that contributed the least (Figure 2).

(Figure 2)

4. Discussion

In this study, we have provided equations to contribute to improving the accuracy of infrastructure datasets in inventories for protected crops.

Four different kinds of greenhouses were assessed: a glass greenhouse, a multi-tunnel greenhouse, a *parral* greenhouse and a low-tunnel greenhouse.

LCA practitioners can use the equations to calculate the amount of the main materials used in the different kinds of greenhouses as a function of the main greenhouse dimensions.

Previous studies on protected crops do not include infrastructure when following standard PAS-2050. Other studies calculate the impact for specific dimensions and the results are only representative of those structures. Special caution should therefore be taken when quantities of materials vary greatly.

When infrastructure is not taken into account in the environmental assessment, the total impact may be between 10% and 30% lower than the real impact (Martínez-Blanco et al., 2011). This represents a drawback when making comparisons with evaluations of open-field crops, which usually have lower productivity.

Comparison with previous studies shows that those values fall within the ranges found in our study. For example, the study by Torrellas et al. (Torrellas et al., 2012a) showed a value of 1.45 kg CO_2 eq·m^{-2}·y^{-1} for a multi-tunnel greenhouse with two vents and walls of polycarbonate sheets and they included transport of materials, while our averages were 1.1 kg CO_2 eq·m^{-2}·y^{-1}, for a polyethylene side walls and 1.27 kg CO_2 eq·m^{-2}·y^{-1} for a polycarbonate side walls without including transport. In the case of the multi-tunnel greenhouse with one vent, Anton (2004) and

Martínez (2011) calculated values of 0.96 kg CO_2 eq·m^{-2}·y^{-1} and 0.98 kg CO_2 eq·m^{-2}·y^{-1}, respectively. These values were also comparable to ours, since our average was 0.97 kg CO_2 eq·m^{-2}·y^{-1}. The comparative study by Russo (2005) of different kinds of greenhouse structures did not provide absolute values, but rather a comparison of three kinds of structures (a. glass; b. plastic and steel; and c. plastic and wood) and showed that, if glass represented a value of 100, the plastic and steel structure represented 52% of that value, and the plastic and wood structure represented 12%. In our case, the mean values for the multi-tunnel greenhouse were between 34% and 38% of the figure for the glass greenhouse, depending on the number of vents, and the mean value for the wood and plastic in the *parral* greenhouse contributed 23%. When the variability of the impact of the different structures was taken into account, Russo's values were comparable to ours.

We referred to Boulard et al. (2011) to calculate CO_2 emissions eq of 4.8 kg CO_2 eq·m^{-2}·y^{-1} and 0.96 kg CO_2 eq·m^{-2}·y^{-1} for the glass greenhouse and tunnel greenhouse, respectively. While the value of Boulard et al. (2011) for the tunnel structure was within our range, their value for the glass greenhouse was above our range. However, their study seems to imply that unspecified materials besides the frame, cover and post footings were included. In addition, Boulard et al. (2011) assumed a life span of 30 years, which is a real value, but does not match the CEN standard (CEN 2001), which is the approach taken in this study. The value for the Venlo glass greenhouse in the study by Montero et al. (2011) was 2.99 kg CO_2 eq·m^{-2}·y^{-1}, which matches our estimate.

This study used the climate change impact category as the only category for comparing different kinds of structures. The same inventory datasets can certainly be used to assess other impact categories commonly used in LCAs in agriculture. For the sake of brevity, we did not do this in our study, but it would make more sense to assess the complete greenhouse crop production cycle, as well as the expansion of different waste management scenarios.

Steel is protected against corrosion by a galvanization process. Galvanized building products (such as those used in greenhouses construction) can be an important diffused source of zinc emissions into the ecosphere: as a result of corrosion, zinc emissions occur (Lupsea et al 2012; Robert-Sainte, P., 2009). In addition, in some areas, rainwater is collected from gutters which can also be zinc contaminated. Nowadays such emissions and their effect on ecotoxicity are not taken into account in LCA studies. This is a subject to be addressed in future studies and included in the calculations of LCIs.

The number of 35 samples selected for the statistical analysis could be increased to achieve an “n” large enough to cover the variance, but we preferred to use the realistic criteria of actual structures. Therefore, the approach taken was to select the most common versions of representative structures and to avoid unusual configurations. The figures in Table 7a and 7b help justify the use of 35 samples, given that including RSD and quality criteria with the pedigree matrix provides a clear idea of the representativeness and completeness of the data.

With the application of the methodology proposed by the ILCD complemented with more specific criteria of the pedigree matrix, most of the components provide some basic data quality. The precision factor depends on the variability of the sample, but high variability should not be equated with high uncertainty. A further revision of ILCD quality criteria is needed to differentiate more clearly between variability and uncertainty. We have included the geometric mean and basic uncertainty in the tables so that other practitioners can choose the quality criteria most appropriate to their case studies (e.g. EC 2013; EU-JRC-IES 2010; Weidema et al 2012).

From the statistical analysis, we have identified the materials that show the greatest variability, such as concrete in glass greenhouses (RSD=72.6), wall covering materials in multi-tunnel greenhouses, (RSD=59.6) and insect-proof screens in *parral* greenhouses (RSD=140.6). This means that special care should be taken with these parts of the inventory because all of them may affect the total impact of the infrastructure by more than 5%.

5. Conclusions

Given the importance of the use of greenhouses in agriculture and the complexity of calculating their environmental impact in life cycle assessments, our aim was to provide a method for a more simplified calculation of the environmental impact of these structures. We have presented simplified models for the four most representative kinds of greenhouses: the glass greenhouse, multi-tunnel greenhouse, *parral* greenhouse and low-tunnel greenhouse. Based on a selection of the materials that contribute the most to the environmental impact of these structures, we have developed equations for calculating the quantity of material used based on greenhouse dimensions. We have also provided statistical and qualitative analysis of the data used in accordance with ILCD criteria (EU-JRC-IES 2010). Applying the equations developed in this study is an easy way to calculate the quantity of materials used to make greenhouses of different dimensions, thus providing a more accurate calculation of greenhouse impact. This analysis also highlights the importance of the different amounts of materials used to build these structures and, therefore, the need to include ranges of uncertainty in environmental analyses.

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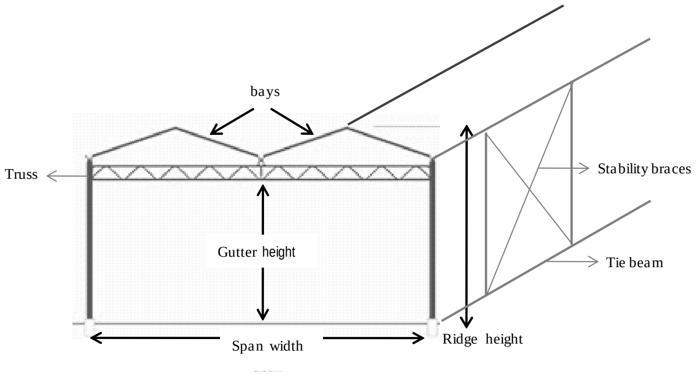
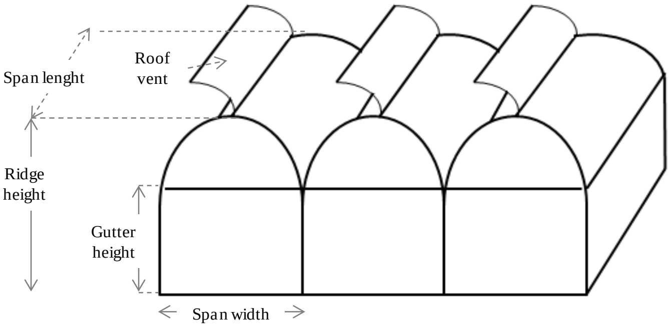
a)


bays
Truss
Stability braces
Gutter height
Tie beam
Span width
Ridge height

b)


Span lenght
Roof vent
Ridge height
Gutter height
Span width

c)

d)

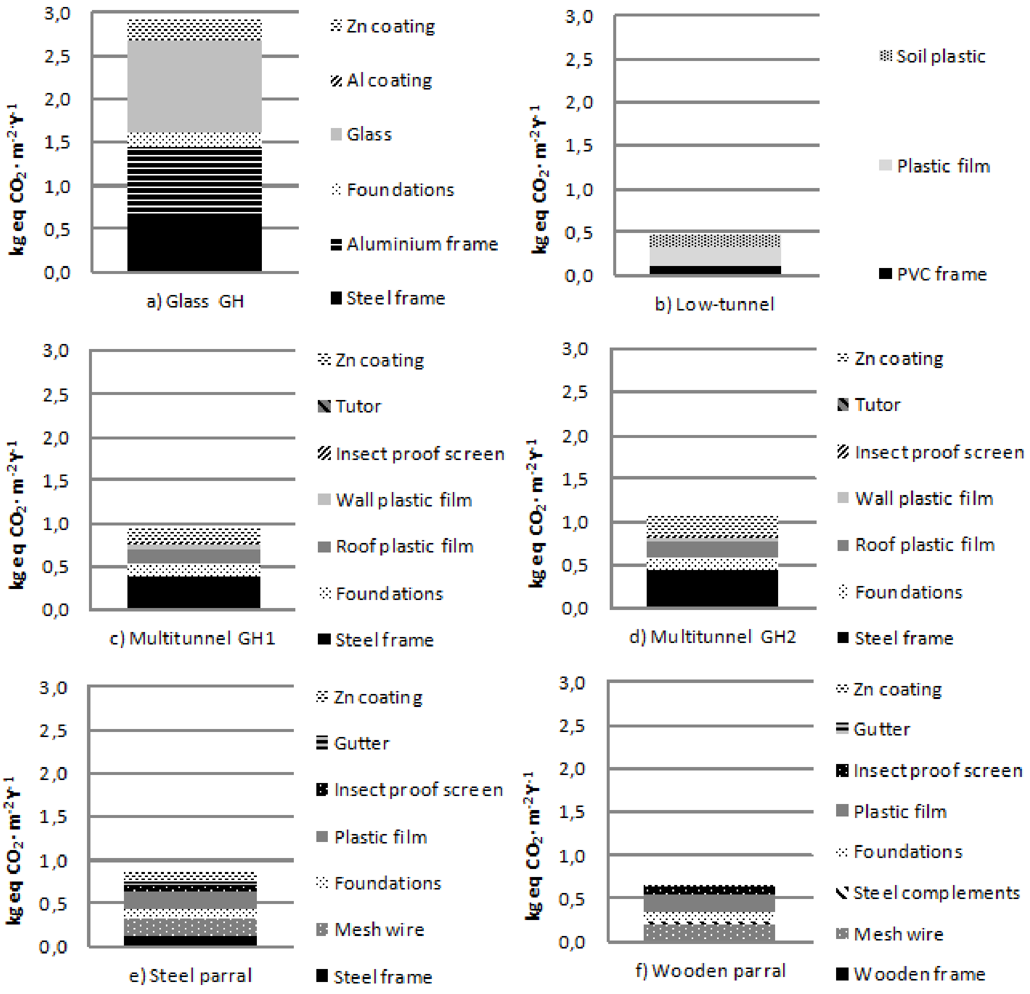


Figure 2. Detail of the different material contributions to the climate change impact category (kg eq. $CO_2 \cdot m^{-2} \cdot y^{-1}$) for a) glass greenhouse (Glass GH); b) Polyvinylchloride low-tunnel (Lowtunnel); c) multi-tunnel greenhouse with 1 opening (Multitunnel GH1); d) multi-tunnel greenhouse with 2 openings (Multitunnel GH2); e) steel frame *parral* greenhouse (Steel parral) and f) wooden frame *parral* greenhouse (Wooden parral).

Table 1. Main dimensions of each greenhouse structure

Type		**Glass**	**Multi-tunnel**	***Parral***	**Low-tunnel**
Area (m^2)	Avg	22,339	11,433	7,710	210.3
	Min	512	432	432	24
	Max	104,000	62,500	22,500	900
Number of spans/ number of bays	Avg	13/2.5	10	8	1
	Min	4/1	3	3	1
	Max	25/4	25	15	1
Span width (m)	Avg	9	8.1	8.3	3.1
	Min	6	6	6	0.8
	Max	12.8	10	10	9
Greenhouse length (m)	Avg	141.3	105.5	95.1	66
	Min	20	24	24	30
	Max	320	250	150	100
Gutter height (m)	Avg	4.4	4.1	2.8	-
	Min	3.2	3.5	1.5	-
	Max	6	4.5	3.5	-
Ridge height (m)	Avg	5	5.4	3.9	1.2
	Min	4	4.2	2.5	0.3
	Max	6.8	5.8	4.5	3.5

Table 2. Quality levels and quality rating for precision quality indicators relative to the standard deviation, RSD, in % (EU-JRC-IES 2010)

RSD	Quality rating	Quality level
<7%	1	Very good
7%-10%	2	Good
10%-15%	3	Fair
15%-25%	4	Poor
>25%	5	Very poor

Table 3. Amount of materials needed for the glass greenhouse expressed as a function of the main greenhouse dimensions

Item	Unit	Symbol	Equation	R²
Steel frame	$kg \cdot m^{-2}$	GF_{st}	$= 48.15 \cdot (P)^{-0.237}$	0.80
Aluminium frame	$kg \cdot m^{-2}$	GF_{Al}	$= 2.5$	
Coating on steel	$m^2 \cdot m^{-2}$	GC_{st}	$= 0.0269 \cdot (GF_{st})+0.3312$	0.99
Coatingon aluminium	$m^2 \cdot m^{-2}$	GC_{Al}	$= 0.034$	
Concrete	$kg \cdot m^{-2}$	GF_C	$= 2.33 \cdot (P)^{-0.94}$	0.99
Glass cover	$kg \cdot m^{-2}$	GG	$= 9.9 \cdot (Sd/S)^{1.31}$	0.91

Note: P: perimeter (m); Sd: developed area (m^2); S: covered area (m^2)

Table 4. Amount of materials needed for the multi-tunnel greenhouse expressed as a function of the main greenhouse dimensions

Item	Unit	Symbol	Equation	R²
Steel frame (one roof vent)	$kg \cdot m^{-2}$	MF_{st1}	$= 47.72 \cdot (V/N)^{-0.24}$	0.84
Coating on steel	$m^2 \cdot m^{-2}$	MC_{st1}	$= 0.064\ MF_{st1} + 0.039$	0.99
Steel frame (two roof vents)	$kg \cdot m^{-2}$	MF_{st2}	$= 53.03 \cdot (V/N)^{-0.23}$	0.82
Coating on steel	$m^2 \cdot m^{-2}$	MC_{st2}	$= 0.056\ MF_{st2} + 0.030$	0.99
Concrete	$kg \cdot m^{-2}$	MF_c	$= 0.37P^{-0.65}$	0.92
Plastic film on roof	$kg \cdot m^{-2}$	MR_f	$= 0.184 \cdot (S_d/S)$	
Polycarbonate walls	$kg \cdot m^{-2}$	MW_{PC}	$= 79.47 \cdot P^{-0.98}$	0.96
Plastic film walls	$kg \cdot m^{-2}$	MW_f	$= 12.67 \cdot P^{-0.98}$	0.96
Insect-proof screens	$kg \cdot m^{-2}$	MS	$= 0.18 \cdot (N \cdot L \cdot O/S)^{0.94}$	0.98

Note: V: volume (m^3); N: number of spans; P: perimeter (m); Surface developed (m^2); S: covered area (m^2);L: greenhouse length (m); O: number of roof vents

Table 5. Amount of materials needed for the parral greenhouse expressed as a function of the main greenhouse dimensions

dimensions

Item	Unit	Symbol	Equation	R²
Steel frame	$kg\cdot m^{-2}$	PF_{st}	$= 15.72\ (S)^{-0.22}$	0.90
Wooden frame	$kg\cdot m^{-2}$	PF_{w}	$= 5.0\ (S)^{-0.173}$	0.81
Concrete f	$kg\cdot m^{-2}$	PF_{c}	$= 0.067\cdot(S)^{-0.28}$	0.86
Steel for vents in wooden frame	$kg\cdot m^{-2}$	PO_{st}	$= 161.12\ (V/N)^{-0.77}$	0.83
Steel wire mesh	$kg\cdot m^{-2}$	PM_{w}	$= 1.326\cdot(V/N)^{-0.082}$	0.89
Coating on steel frame	$m^{2}\cdot m^{-2}$	PC_{st}	$= 0.056\ (PS_{st})^{0.50}$	0.83
Coating on steel wire mesh	$m^{2}\cdot m^{-2}$	PC_{w}	$= 0.0992\cdot(PM_{w})^{1.775}$	0.91
Plastic film cover	$kg\cdot m^{-2}$	PC_{f}	$= 0.374\cdot(S)^{-0.058}$	0.92
Plastic gutter, polypropylene	$kg\cdot m^{-2}$	PG_{p}	$= 1.176\ (V/N)^{-0.27}$	0.85
Insect-proof screens	$kg\cdot m^{-2}$	PS	$= 213.01\cdot(S)^{-0.976}$	0.99

Note: V: volume (m^3); N: number of spans; S: covered area (m^2)

Table 6. Amount of materials needed for the tunnel greenhouse expressed as a function of the main greenhouse dimensions

Item	Unit	Symbol	Equation	R²
Hoops, Steel	$kg\cdot m^{-2}$	TA_{st}	$= 1.012\cdot(S_d/D)^{0.23}$	0.996
Hoops, PE	$kg\cdot m^{-2}$	TA_{PE}	$= 0.118\cdot(S_d/D)^{0.23}$	0.996
Hoops, PVC	$kg\cdot m^{-2}$	TA_{PVC}	$= 0.18\cdot(S_d/D)^{0.23}$	0.996
Plastic film	$kg\cdot m^{-2}$	TC_{f}	$= 0.184\cdot(S_d/S)$	

Note: Sd: Surface developed (m^2); D: Hoops diameter (m); S: covered area (m^2)

Table 7a. Components, average amount per square meter and year, life span, geometric mean (μ), variance of log transformed data (σ_g^2), relative standard deviation (RSD), scores relative to precision (P) and technological representativeness (TeR), data quality rating (DQR) and data quality level (DQL) in accordance with ILCD criteria for each component of glass and multitunnel greenhouse structures. DQL="high quality", if DQR<1.6; DQL="basic quality", if 3<DQR> 1.6 and DQL="data estimate", if 4<DQR>3

Materials Greenhouse Structure	**Units**	**Comments**	**Amount·$y^{-1}\cdot m^{-2}$**	**Life span (y)**	**μ**	**σ_g^2**	**RSD**	**P**	**TeR**	**DQR**	**DQL**
Glass											
Steel, electric, un- and low-alloyed, at plant/RER +Drawing of pipes, steel/RER	kg	frame	$7.63\cdot10^{-01}$	15	$7. 52\cdot10^{-01}$	0.026	19.1	4	1	2,5	BASIC
Aluminium, secondary, from old scrap, at plant/RER + Aluminium product manufacturing, average metal working/RER	kg	frame	$1.69\cdot10^{-01}$	15	$1.68\cdot10^{-01}$	0.012	11.5	3	1	2,0	BASIC
Concrete, normal, at plant/CH	m3	foundation	$6.18\cdot10^{-04}$	15	$5.03\cdot10^{-04}$	0.358	81.9	5	2	3,1	DATA ESTIMATE
Flat glass, uncoated, at plant/RER + Tempering, flat glass/RER	kg	covering material	$8.82\cdot10^{-01}$	15	$8.76\cdot10^{-01}$	0.014	13.1	3	1	2,0	BASIC
Powder coating, aluminium sheet/RER	m^2	frame	$2.24\cdot10^{-03}$	15	$2.20\cdot10^{-03}$	0.045	18.5	4	1	2,5	BASIC
Zinc coating, pieces/RER	m^2	frame	$4.26\cdot10^{-02}$	15	$4.25\cdot10^{-02}$	0.007	9.3	2	1	1,5	HIGH Q
Multi-tunnel, 2 vents											
Steel, electric, un- and low-alloyed, at plant/RER +Drawing of pipes, steel/RER	kg	frame	$5.23\cdot10^{-01}$	15	$5.17\cdot10^{-01}$	0.025	17.0	4	2	2.6	BASIC
Zinc coating, pieces/RER U	m^2	frame	$3.20\cdot10^{-02}$	15	$3.17\cdot10^{-02}$	0.017	14.0	3	2	2.1	BASIC
Polyethylene, HDPE, granulate, at plant/RER +Extrusion, plastic film/RER	kg	insect-proof screen	$1.58\cdot10^{-02}$	3	$1.56\cdot10^{-02}$	0.021	14.7	3	2	2.1	BASIC
Multi-tunnel, 1 vent											
Steel, electric, un- and low-alloyed, at plant/RER +Drawing of pipes, steel/RER	kg	frame	$4.48\cdot10^{-01}$	15	$4.42\cdot10^{-01}$	0.026	17.3	4	2	2.6	BASIC
Zinc coating, pieces/RER U	m^2	frame	$3.11\cdot10^{-02}$	15	$3.08\cdot10^{-02}$	0.018	14.3	3	2	2.1	BASIC
Polyethylene, HDPE, granulate, at plant/RER +Extrusion, plastic film/RER	kg	insect-proof screen	$7.89\cdot10^{-03}$	3	$7.81\cdot10^{-03}$	0.021	14.7	3	2	2.1	BASIC
Multi-tunnel, common parts											
Polyethylene, LDPE, granulate, at plant/RER +Extrusion, plastic film/RER	kg	roof covering material	$6.74\cdot10^{-02}$	3	$6.70\cdot10^{-02}$	0.0003	1.8	1	3	2.0	BASIC
Polyethylene, LDPE, granulate, at plant/RER +Extrusion, plastic film/RER	kg	wall covering material	$1.66\cdot10^{-02}$	3	$1.43\cdot10^{-02}$	0.284	59.6	5	3	3.2	DATA ESTIMATE
Polycarbonate, at plant/RER +Extrusion, plastic film/RER	kg	wall covering material	$3.12\cdot10^{-02}$	10	$2.69\cdot10^{-02}$	0.284	59.6	5	2	3.1	DATA ESTIMATE
Concrete, normal, at plant/CH	m^3	foundation	$5.92\cdot10^{-04}$	15	$5.52\cdot10^{-04}$	0.133	43.1	5	2	3.1	DATA ESTIMATE

Table 7b. Components, average amount per square meter and year, life span, geometric mean (μ), variance of log transformed data (σ_g^2), relative standard deviation (RSD), scores relative to precision (P), technological representativeness (TeR), data quality rating (DQR) and data quality level (DQL) in accordance with ILCD criteria for each component of *parral* and low-tunnel greenhouse structures. DQL="high quality", if DQR<1.6; DQL="basic quality", if 3<DQR> 1.6 and DQL="data estimate", if 4<DQR>3

Materials Greenhouse Structure	**Units**	**Comments**	**Amount·$y^{-1}\cdot m^{-2}$**	**Life span (y)**	**μ**	**σ_g^2**	**RSD**	**P**	**TeR**	**DQR**	
***Parral*. steel frame**											
Steel. electric. un- and low-alloyed. at plant/RER +Drawing of pipes. steel/RER	kg	Steel frame	$1.57\cdot10^{-01}$	15	$1.53\cdot10^{-01}$	0.044	23.3	4	2	2.6	BASIC
Zinc coating. pieces/RER	m^2	Steel frame	$5.56\cdot10^{-03}$	15	$5.52\cdot10^{-03}$	0.013	11.6	3	2	2.1	BASIC
***Parral*, wooden frame**											
Sawn timber. raw. forest debarked. u=70%. at plant RER	kg	Wooden frame	$7.61\cdot10^{-02}$	15	$7.50\cdot10^{-02}$	0.029	17.5	4	2	2.6	BASIC
Steel. electric. un- and low-alloyed. at plant/RER +Drawing of pipes. steel/RER	kg	Complements	$3.07\cdot10^{-02}$	15	$2.61\cdot10^{-02}$	0.302	68.3	5	2	3.1	DATA ESTIMATE
Zinc coating. pieces/RER	m^2	Steel frame	$1.8\cdot10^{-03}$	15	$1.8\cdot10^{-03}$	0.0003	1.72	1	2	1.5	HIGH Q
***Parral*. common parts**											
Concrete. normal. at plant/CH	m^3	foundations	$4.13\cdot10^{-04}$	3	$3.97\cdot10^{-04}$	0.073	31.1	5	2	3.1	DATA ESTIMATE
Polyethylene. LDPE. granulate. at plant/RER +Extrusion. plastic film/RER	kg	covering material	$7.56\cdot10^{-02}$	3	$7.55\cdot10^{-02}$	0.003	5.5	1	3	2.0	BASIC
Polyethylene. HDPE. granulate. at plant/RER +Extrusion. plastic film/RER	kg	insect-proof screen	$2.47\cdot10^{-02}$	3	$1.56\cdot10^{-02}$	0.763	140.6	5	2	3.1	DATA ESTIMATE
Polypropylene. granulate. at plant/RER + Injection moulding/RER	kg	gutter	$2.42\cdot10^{-02}$	6	$2.37\cdot10^{-02}$	0.039	21.5	4	2	2.6	BASIC
Wire drawing. steel/RER	kg	mesh to support plastic film	$4.68\cdot10^{-02}$	15	$4.67\cdot10^{-02}$	0.003	5.9	1	2	1.5	HIGH Q
Zinc coating. wire/RER	m^2	mesh to support plastic film	$3.56\cdot10^{-03}$	15	$3.54\cdot10^{-03}$	0.012	11.2	3	2	2.1	BASIC
Low-tunel											
Polyethylene. LDPE. granulate. at plant/RER +Extrusion. plastic film/RER	kg	covering material	$8.75\cdot10^{-02}$	3	$8.7\cdot10^{-02}$	0.004	6.03	1	3	2.0	BASIC
Steel. electric. un- and low-alloyed. at plant/RER +Drawing of pipes. steel/RER	kg	Steel frame	$1.72\cdot10^{-01}$	10	$1.6\cdot10^{-01}$	0.099	31.1	5	2	3.1	DATA ESTIMATE
Polyvinylchloride. granulate. at plant/RER + injection moulding	kg	PVC frame	$3.05\cdot10^{-02}$	10	$2.9\cdot10^{-02}$	0.099	31.1	5	2	3.1	DATA ESTIMATE
Polyethylene. HDPE. granulate. at plant/RER + injection moulding	kg	HDPE frame	$2.01\cdot10^{-02}$	10	$1.9\cdot10^{-02}$	0.099	31.1	5	2	3.1	DATA ESTIMATE
Polyethylene, LDPE, granulate, at plant/RER U+Extrusion, plastic film/RER U	kg	soil covering material	$6.13\cdot10^{-02}$	3	$6.13\cdot10^{-02}$			1	3	1.8	BASIC