Bioenerg. Res. (2015) 8:1769–1777
DOI 10.1007/s12155-015-9630-1

How Much Yield Should We Expect from Fast-Growing Plantations for Energy? Divergences Between Experiments and Commercial Willow Plantations

Blas Mola-Yudego [1,2] · **Olalla Díaz-Yáñez** [3] · **Ioannis Dimitriou** [2]

Published online: 5 June 2015

Abstract How representative are yields from experimental plots compared to large-scale commercial implementation? This study analyses the yields of fast-growing willow plantations for energy reported in experimental trials in Sweden during the period 1980–2012 compared with those from commercial willow plantations for the period 1986–2006. The study reviews 16 academic publications, which include 466 records from experimental plots, and records from 2073 commercial plantations across the country. The average yield recorded from experiments was 7.7 odt ha^{-1} $year^{-1}$, compared to commercial plantations' yields 2.6 and 4.2 odt ha^{-1} $year^{-1}$ for the first and second rotations, respectively. The measured area of the experimental plots seems to have an effect in the overestimation of the average yields, which can be attributed to extrapolation errors. In addition, to explain the broad differences between yield estimates, we identify the following as potential factors: near-optimal management practices and choice of land age differences and rotation lengths, edge effects, measurement methods, harvesting losses, increased mortality, and increased probability of hazard. The results can help to rationalize the expectations derived from experiments and to a more realistic planning of future plantation schemes.

Keywords Biomass · Bioenergy · Short rotation forestry · Energy crops

✉ Blas Mola-Yudego
blas.mola@slu.se; blas.mola@skogoglandskap.no

[1] Norwegian Forest and Landscape Institute, P.O. Box, 115, 1431 Ås, Norway

[2] Department of Crop Production Ecology, Swedish University of Agricultural Sciences (SLU), P.O. Box 7016, SE-75007 Uppsala, Sweden

[3] School of Forest Sciences, University of Eastern Finland, PO Box 111, 80101 Joensuu, Finland

Introduction

How much biomass should be expected from energy crops once they reach commercial stage? A good yield prognosis is an important tool for reliable energy policies and for a successful introduction of energy crops [1]. Accurate yield estimates at local or national level are required, e.g., for the construction of scenarios (e.g., [2]), policy incentives (e.g., [3]), profitability estimates (e.g., [4–6]), or even environmental assessment (e.g.,[7, 8]). However, many energy crops are to a certain extend new cropping systems and lack the necessary commercial experience to get empirical data. For this reason, initial estimates and models must rely on results from experimental plots or trials.

Among lignocellulosic energy crops, this has been the case for short rotation plantations. Such plantations are based on fast-growing woody species (such as poplar and willow) established on agricultural land. The plantations are intensively managed for the provision of biomass for energy, and for the several environmental benefits provided: diversification of farm crops, positive effects on rural economies, role as vegetation filters (e.g., [6, 9, 10]), better water and soil quality than agricultural crops (e.g., [11, 12]), phytoremediation of soils [13] reduction of CO_2 emissions through the production of biomass for fossil substitution, and CO_2 storage in vegetation and soil (e.g., [14]).

All these benefits have lead to their development and consideration as viable energy crops. In general, many estimates have relied on trials and experiments for the construction of models (e.g., [15]) or for spatial supply of biomass (e.g., [16]). Others have used a limited number of samples and extrapolate to the plantation area for the validation of process models (e.g., [17]), or have been estimating yields based on general averages (e.g., [18]).

On the other hand, experience shows that the materialization of these yields is seldom achieved. In Finland [19] and in Sweden [20], the analysis of existing data showed that yields from commercial plantations were much lower than expectations based on trials. This was attributed to poorer average site quality, poor clone-site matching, limited fertilization, disease susceptibility, and weed competition. In this line, several authors have questioned the representativeness of experimental plots for large-scale plantations. Zavitkovsky [21] and Hansen [22] made a comparison for poplar yields, showing the divergences between yields from small plots and commercial results, and Searle and Malins [23] pointed at the same direction.

At present, Sweden provides the necessary empirical experience, as short rotation willow plantations have been cultivated since the 1980s. Sweden has been for the last decades the leader in Europe, reaching about 13.000–16,000 ha planted with commercial plantations [24], which allows us to compare to which extend the commercial experience matches the experimental results. The aim of this study is to assess the yield levels reported by trials and experimental plots during the period 1980–2010 in Sweden, compared to the performance of commercial plantations during the same period. The analysis performed should contribute to a realistic and cost-efficient planning of energy crop schemes in other countries with similar future energy planning.

Material and Methods

Description of the Data

The analyses include records from experimental plots as well as commercial plantations. For the experimental plots, a database of publications was constructed using academic search engines, and priority was given to published journal papers on the field. The search aimed to retrieve Swedish experiments based on willow cultivation for energy uses in short rotation schemes. The compilation of the data was performed in 2012, and resulted in 16 publications (Table 1). Those included records from trials from Larsson and Dobrzeniecki [40] that were also retrieved, although in this case, as there was no available information concerning total area planted, spacing or treatments, they were analyzed separately.

From each publication, information concerning the experimental set-up was structured, extracting figures concerning the reported yield of the experiment (under the different treatments) as well as the establishment of the trials, including the following: location of the experiments (Fig. 1), area of the plot, area of the plantation, clones used, dates when the plantation was established, etc.… In the context of the analysis, *measured area* was defined as the area associated to each individual yield (the area where the plants were measured or harvested, resulting in a yield estimate). *Plot area* was defined as the area subject to the same treatment, and *plantation area* was defined as the total area of the plantation, when available. In many cases, these definitions had to be estimated (e.g., by dividing the plot area by the number of samples, by estimating the area covered by measured plants using the planting density).

Data concerning commercial plantations were provided by Lantmännen Agroenergi AB (formerly known as Agrobränsle AB), which manages planting and administrates the harvesting of willow plantations. The data consisted in harvested records from each plantation (i.e., leafless above-ground dry mass). In this case, plot area and plantation area referred to the same area. Data with inconsistent records were excluded from the calculations. All plots were geo-referenced to at least 1 km precision. They covered the area from 55° 20′ N to 61° 29′ N and from 11° 33′ E to 18° 56′ E (Fig. 1), resulting in 2073 plantations during the period 1986–2005. All plantations studied had been cut back, in most cases after the first growing season. The annual yield was calculated by dividing the harvest of each rotation (i.e., cutting cycle) by the number years since the cutback or the last harvest (i.e., rotation length).

Methods

The *measured area* associated to each yield was used in the calculations in the natural logarithm form, and the focus of the analysis was aimed to find qualitative differences between large and small measured areas. The mean yields from experiments and commercial plantations were compared using a *t* test. The relationship between yield and measured area was explored using regression. A sensitivity analysis was performed, recalculating the means and relationships from the publications, excluding one at time. Trends along time were also explored.

The yield ranges were compared in categories, similarly to Hansen [22]. The results from trials and experiments were divided in two groups, aiming at having a balanced number of estimates between the groups: small (measured area up to 200 m^2) and large (measured area larger than 200 m^2). The commercial plantations were further grouped for 1st and 2nd rotations, and for those planted before 1996 and the rest. For each group, the upper range was calculated using the 25 % of the best yields, and the lower range, with the 25 % of the lowest yields. As a reference, the average of the 10 % best yields was also included.

Table 1 Literature sources (16) and descriptors of the experiments included in the study. Mean and maximum (max) expressed in odt ha^{-1} year^{-1}

Reference	Lat (N)	Long (E)	Estimates retrieved	Mean	Max	Main aim of the study
[25]	56.93	12.38	7	14.3	17.0	Determine biomass production efficiency under different irrigation-fertilization systems.
[26]	56.93	12.38	7	16.3	22.7	Maximize biomass production by combining fertilization methods with different irrigation techniques.
[27]	59.48	16.07	159	6.4	11.3	Biomass production for different density, rotation cycles and pure vs. mixed stands.
[28]	59.82	17.67	6	9.2	10.7	Biomass production for different rotation cycles.
[29]	55.75	13.03	20	11.0	16.2	Stem growth calculations for different fertilization regimes.
	58.33	15.67	20	6.0	8.7	
	58.63	16.10	20	8.9	13.4	
	59.42	15.58	16	6.6	11.9	
	59.82	16.78	4	9.1	10.0	
[30]	59.48	16.07	32	3.4	4.7	Determine an optimal plant arrangement regarding biomass yield as well as traceability with tractors and machinery for different plant densities.
[31]	56.00	13.00	2	4.9	5.1	Early biomass production and stand dynamics under different systems.
[9]	56.48	13.00	5	9.9	10.8	Establish a willow vegetation filter for nitrogen-polluted agricultural drainage water.
[32, 33]	59.62	16.80	48	7.4	9.8	Comparing destructive vs. non-destructive measurements of different clones.
[34]	59.82	17.67	12	4.3	8.0	Compare growth data from different trials and clones under different environmental conditions.
	57.60	18.45	6	4.4	5.2	
[35]	59.17	17.64	12	9.2	17.8	Evaluate the effect of water availability on stand-level productivity.
[36]	59.82	17.77	5	14.8	15.9	Estimation of wood fuel quality under different management practices such as the frequency of harvests and the fertilization with wastes.
	59.82	17.77	5	11.3	12.9	
[37, 38]	59.69	17.28	16	9.1	14.9	Determine biomass production under different management regimes.
	59.53	17.05	16	11.7	19.2	
	59.97	17.56	16	5.7	11.6	
	60.02	17.31	16	10.2	13.5	
	59.98	17.58	16	12.2	17.4	
[39]			9	7.2	8.58	Review of the performance of several trials for willow varieties released in the market. The data is aggregated by clones.

Results

The distribution of yields was different for the commercial plantations and the trials (Fig. 2). There were in total 2073 records (1610 for 1st rotation, and 1524 for the 2nd rotation, not always overlapping) from commercial plantations and 466 records from trials and experiments. The yield ranges of the experiments and trials were wider than in commercial plantations. The mean yield from experimental plots was significantly higher than from commercial plantations (t=28.4481, p *value*<0.001). The average for the 1st rotation in the commercial plantations (harvested records) was 2.6 odt ha^{-1} year^{-1} and for the 2nd rotation, 4.2 odt ha^{-1} year^{-1}, whereas for experimental plots was 7.7 odt ha^{-1} year^{-1}.

The average measured area for yields from experimental plots was 38.86 m^2, and the average plantation area was 4.34 ha (Fig. 3). There was an inverse trend between the performance of the trials and the area measured (Fig. 3c) that was significant (F=24.55 p value<0.001, slope=−0.974). Similarly, it was also detected an inverse trend concerning the yield records from commercial plantations and the size of those plantations (F=5.705, p value=0.017, slope=−0.122).

Since a single publication can have a strong effect on the means and trends, the mean and the trends (Fig. 3) were iteratively calculated, excluding a publication each time. The results showed little variation: for the mean, the highest value was 8.33 odt ha^{-1} year^{-1} (excluding [27]) and the lowest was 7.24 odt ha^{-1} year^{-1} (excluding [37]). Concerning the relationship with measured area, it was significant in all cases (highest p value< 0.005, excluding [26], otherwise p value<0.001).

The evolution along time showed yield improvements in the commercial plantations (Fig. 4) in parallel with

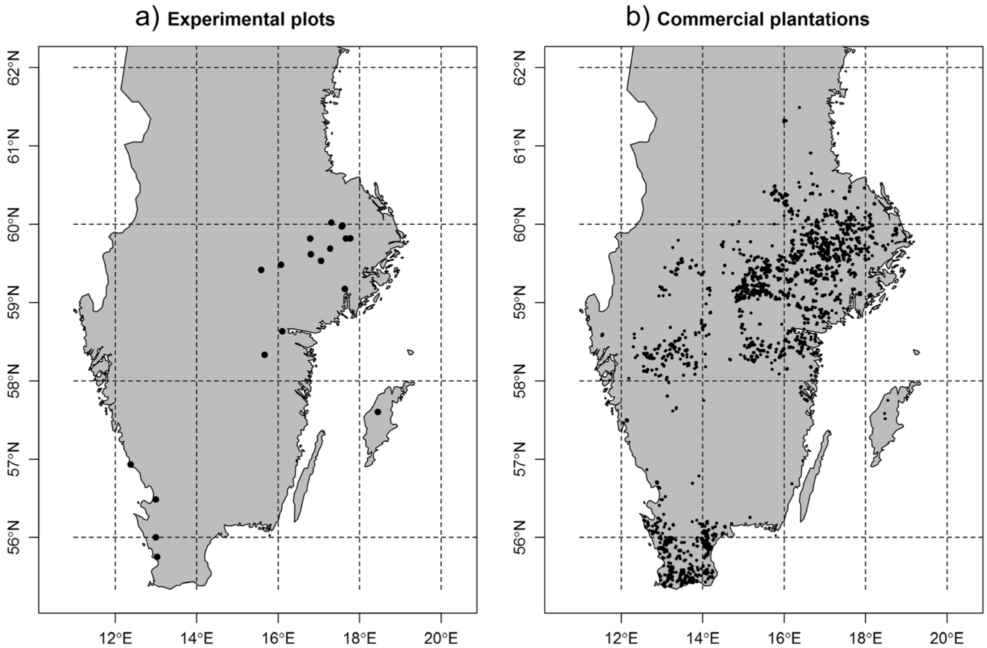

Fig. 1 Map of Sweden showing the locations of the experimental plots (N=23, left) and the commercial willow plantations (N=2073, right) included in the study

new varieties released to the market and the results from experiments, although this tendency was not as pronounced.

Finally, the ranges of the experimental plots and the commercial plantations were analyzed as a continuum, similarly to Hansen [22]. (Fig. 5). The lines show the range between the lower quartile (average of the 25 % lowest results) and the upper quartile (average of the 25 % best results) representing the most frequent values. For the whole of commercial plantations, this resulted in a lower quartile of 1.4 odt ha^{-1} year^{-1} to a higher quartile of 5.8 odt ha^{-1} year^{-1}. For the whole of experimental plots, the lower quartile was 4.12 odt ha^{-1} year^{-1} and a higher quartile of 10.33 odt ha^{-1} year^{-1}. There were, however, important differences between the 1st and the 2nd

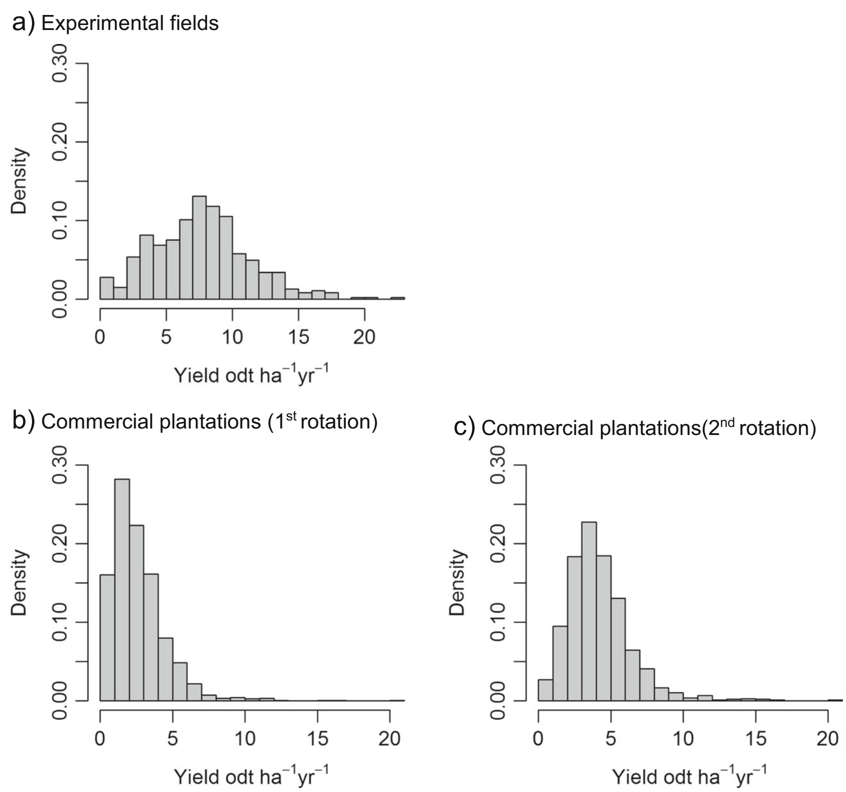

Fig. 2 Histograms for yield (odt ha^{-1} year^{-1}) resulting from: **a** trials (N=466) and from the **b** first and **c** second rotations from commercial plantations (N=2073) in Sweden

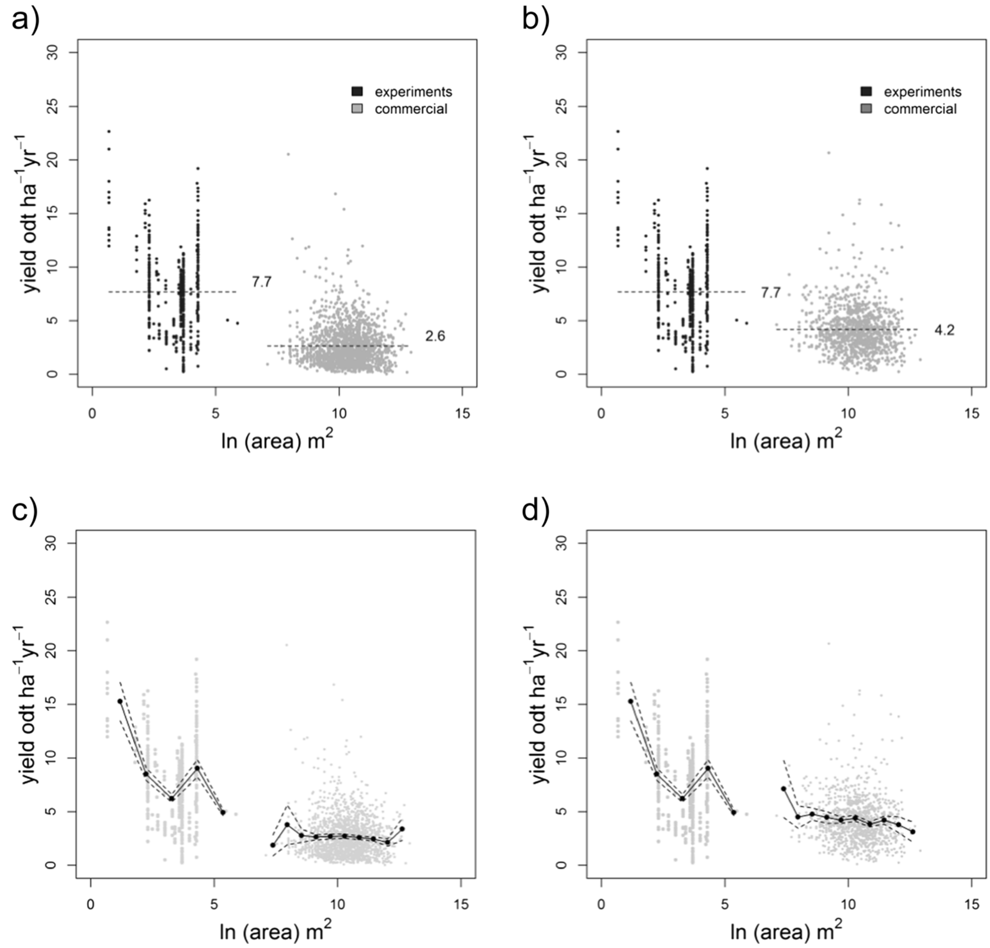

Fig. 3 Yield as a function of the measured area: mean yield (odt ha^{-1} $year^{-1}$) for experimental plots and commercial plantations related to the natural logarithm of the area measured for the yield record (ha). Plantations include the yield results of the **a** 1st rotation and **b** the 2nd rotation. **c** Moving average for experimental plots (5 tiles) and commercial plantations (10 tiles) for the **c** 1st rotation and **d** the 2nd rotation. In **c**, **d**, discontinuous lines represent 2 x Std. Error. Measured area ranges: 1.96 to 357 m^2 (experimental plots) and 0.12 to 40.6 ha (commercial plantations)

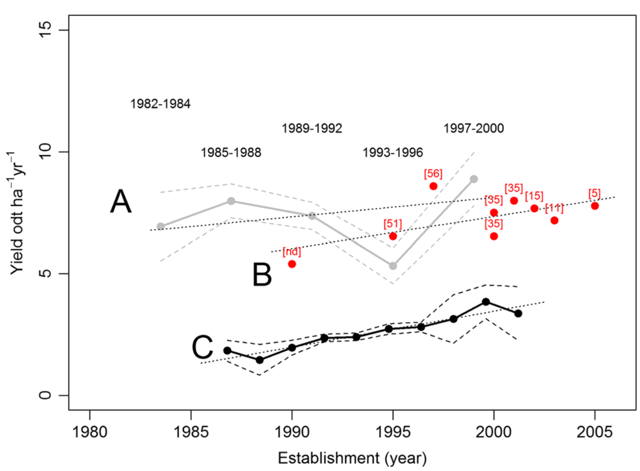

Fig. 4 Average yields from willow fast-growing plantations in Sweden along time. **a** Averages from trials in five periods, by year of the trial establishment and overall trend (t: 7.488, $p<0.001$). **b** Average yield of new varieties by year of release, for the first rotation (length: two years); in brackets: number of trials used for the average [40], and trend of the averages (t: 2.143, $p=0.069$) **c** trend of the yields from commercial plantations during the first rotation, by year of plantation establishment (t: 3.862, $p<0.001$)

rotation, and between those plantations established before 1996 and after that year. Concerning experimental plots, there were differences in the ranges according to the area measured (the threshold was arbitrarily set at 200 m^2).

The highest 10 % of the records were 8.21 odt ha^{-1} $year^{-1}$ for commercial plantations (corresponding to those planted after 1996, 2nd rotation) and 13.7 odt ha^{-1} $year^{-1}$ for experimental plots (corresponding to those whose measured area was smaller than 200 m^2) The analogous values using the highest 5 % of the records would be 9.93 and 17.38 odt ha^{-1} $year^{-1}$, respectively.

Based on these ranges, we propose four categories of yield levels: *factual* would correspond to those levels that have already been reached in commercial experience and that the results show as frequent and therefore reliable estimates. That would include yields up to 5.8 odt ha^{-1} $year^{-1}$. *Best factual* would correspond to those yield levels that have also been reached in commercial experience, but much less frequently, and would include yields up to 8.2 odt ha^{-1}. These levels would configure two realistic scenarios of what can be expected from commercial plantations in Sweden. The category *potential* would entail those yield levels that have been frequently found in experimental plots, although only

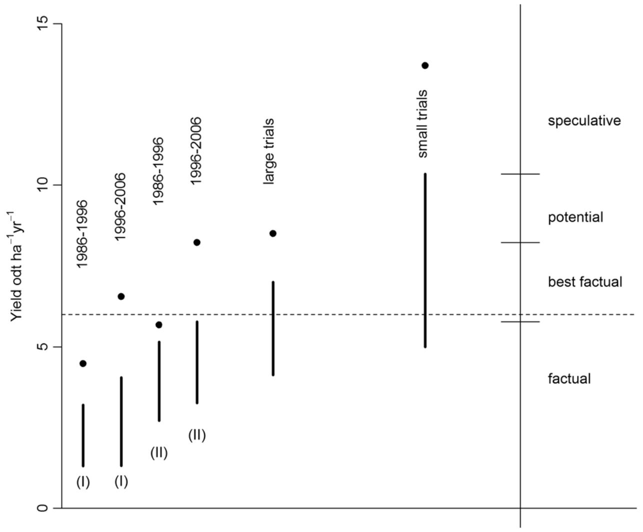

Fig. 5 Yield level ranges in fast-growing plantations from commercial plantations, and experimental plots. *I* 1st rotation, *II* 2nd rotation. The *lines* show the range between the upper quartile (average of the 25 % best results) and the lower quartile (average of the 25 % worst results). The *points* represent the average of the 10 % best records in each group. The years represent the period when the plantations were established, in two groups: 1986–1996 and 1996–2006. The segments on the right propose four categories of yield levels: factual and best factual (those yields have been reached in commercial experience), potential (those yields have often been reached in small trials), and speculative (those yields have been reached in small trials, but seldom). The *horizontal line* refers to a level of 6 odt ha^{-1} year^{-1} which corresponds to the estimated threshold of profitability in Sweden [5, 6]

exceptionally in commercial plantations, and would reach up to 9.9 odt ha^{-1}. Finally, the category *speculative* would go beyond this threshold and would cover those yield levels that have been reported in academic literature, but are rather exceptional.

Discussion

This study focused on the assessment of yield levels reported by trials and experimental plots during the period 1980–2010 in Sweden, compared to the performance of commercial plantations during the same period. Concerning the reliability of the data, it was difficult in some cases to retrieve all the potential information about the experiment set-up, due to missing information about how the averages were calculated. Concerning the commercial plantations, some human errors or missing values were detected in the records from commercial plantations and were excluded from the calculations. However, in the case of experimental plots, all data relied on academic publications, which are, as such, a source of contrasted information and verifiable. In the case of commercial plantations, the data covers reported harvested yields of about 60 % of the area planted in Sweden during the period studied.

The results show that the yields reported from experimental plots did not represent the actual yields obtained in commercial experience, confirming previous studies: Zavitkovski [21] found large overestimations due to the edge effect of small plots. Hansen [22] showed that the production levels derived from small-plot experiments could be 4 to 7 times higher than the average yields from plantations. Searle and Malins [23] reflected the same concern. The results of this study point at the same direction, although the overestimation is in general more conservative than in previous research, especially when the yields result from large measured areas.

In this sense, the size of the measured area seems to be an important variable, although it must be taken as a qualitative factor, since it is rather difficult to estimate with precision the actual area measured associated to each yield estimate. The use of the logarithm scale was proposed in order to retrieve a rather qualitative estimate, reducing the effect of the extreme differences: in some cases, some yield estimates corresponded to a few plants measured (e.g., ranging 1–10 m^2), in other cases, to the whole plot area (e.g., range 10–10^2 m^2), and alternatively to the whole plantation area (e.g., range 10^4 m^2). The analysis showed that a rough division between "large" and "small" measured areas around the 10^2 m would be worthy of further exploration. Although it must be confirmed whether this is a specific effect of the plots analyzed or a general one, similar findings showing great differentiation of willow yields based on plot size were reported by Searle and Malins [23]. In addition to the effects associated to the size of the plot, the effect due to measured area could be explain by extrapolation errors: a sort of *naïve extrapolation* of measured yields in small areas in order to produce estimates at plantation level can accumulate large measurement errors. In addition, small variations in the assumptions of area cover can result in large overestimations. The results of our study show that reported yields resulting from very few samples or small measured areas (less than *ca.* 200 m^2) should be treated very cautiously, taking into account that they may overestimate yield performance whereas larger experiments seem to be more representative.

In general, the overall yield overestimations can be attributed to several factors. Among others, we propose the following: (1) Near-optimal management practices and choice of land occurring in experimental trials compared to management of commercial fields [19, 20], as in some cases, optimal yield performance or establishment on optimal land does not lead to the highest profitability [20] and it is not preferred by the farmers [6]; (2) Edge effects of small-sized trials, as the edge effect can result in much higher yields [21]; (3) Differences in age when comparing experimental plots with commercial plantations, e.g., experimental plots usually imply shorter rotations (due to high implied management costs for long-term experiments) compared to commercial plantations that are grown for longer rotations: the average rotation length was 5.9 and 4.5 years for the first and second cutting cycles, respectively [20], whereas experimental plots are often harvested earlier (2–4 years) to be cost-efficient; (4) Different measurement methods used in trials and commercial fields (e.g., destructive vs non-destructive); (5) Losses while harvesting commercial fields: results from short rotation poplar plantations in Italy reported 0.6 odt ha^{-1} in harvesting losses [38], whereas in experimental plots, estimates often refer to standing biomass or the harvest is done manually minimizing the losses; (6) Increased mortality and hazard in large commercial fields as they are tended for longer time frames; (7) Extrapolation errors from limited measured area; and (8) Last but not least, academic biases, as experiments that resulted in low performance or failure are often not reported, e.g., in Tahvanainen and Rytkönen [19], 19 out of 35 plantations were not reported as they failed and were excluded from the analysis. In the analyzed data, at least one plantation failed due to frost [34] and was not included in the calculations. In other cases, when the failure happens in the middle of the treatment (e.g., [27]) it is often reported or included in the analysis, although many other trial or partial failures may simply be never published.

It is rather difficult to specify which of these factors are the most responsible for the yield overestimations, and it is reasonable to assume that combinations of them occur. It must be taken into account that there are important differences in the set up of the trials and in the objectives of each study that obviously affect the yield levels. In some cases, some actions are deliberately taken to enhance production and, by research definition, challenge standard practices in order to improve the current yields, e.g., use of intensive fertilization and irrigation experiments, higher densities, new clones to be tested, etc. However, for the purposes of the analysis, the differences in set-up are not relevant: the analysis focuses as, generically, these yields are a source of reliable information to deliver accurate estimates at commercial level. This is especially important, as several models and calculations make use of experimental results as a basis for prognosis or for the quantification of biomass production scenarios for energy crops as a future energy solution to replace fossil fuels (e.g., [41–44]).

On the other hand, we must have into account that yields from the first commercial plantations do not reach the optimal levels: At the same time that experimental plots can overestimate yield performance, initial results from the first plantations established can underestimate it (due to lack of proper tending, as observed in [20, 40, 45]). In this sense, to a certain extent, results from small-size trials can serve as indicators of the potential upper yield limit that can be reached in the future or in case of best-practice management in commercial plantations. Therefore, yield models using such yields as background data are in a sense correct (e.g., as in Aylott et al. [16]) simply indicating that they do not reflect the initial nor current situation but a potential (future) scenario of higher commercial yields. This is strengthened by the fact that besides a measured-size trend (as yields from larger measured area get closer to the performance of commercial plantations), the results show a *chronological* trend towards higher yields in commercial willow plantations, e.g., higher yields during the latter years compared to older plantations, as observed by Mola-Yudego [45].

Judging from the findings, a rationalization of the projections for willow is possible, stressing that scenarios based on small-size trials or limited measurements reflect the highest potential range rather than an expected near-future performance at commercial level. In the case of large-size trials, using qualitative bias correction factors, reducing the expectations to at least 50 % would provide realistic prognosis for commercial yields. Large-scale experiments can therefore be regarded as a window to the feasible future for willow energy plantations.

We feel that our findings are with high probability applicable not only for willow but also other lignocellulosic crops that were identified for their potential to deliver biomass for energy, confirming reported overestimations [23], and will almost certainly be the case in several countries where replacement of fossil fuels is identified as a political target. Such yield differences need to get known and be shared with policymakers, investors, and other non-specialists who may expect commercial-scale yields being as high as those in field trials. This will enable to avoid false impressions and expectations when broader implementation of lignocellulosic energy crops will not result in projected outcomes.

Acknowledgments We thank Assoc. Prof. Pär Aronsson for his help discussing the ideas of the manuscript. We would like to extend our gratitude to the editor and anonymous reviewers for their valuable comments.

References

1. Mola-Yudego B, Dimitriou I, González-García S, Gritten D, Aronsson P (2014) A conceptual framework for the introduction of energy crops. Renew Energy 72:29–38. doi:10.1016/j.renene.2014.06.012
2. Bauen AW, Dunnett AJ, Richter GM, Dailey AG, Aylott M, Casella E, Taylor G (2010) Modelling supply and demand of bioenergy from short rotation coppice and Miscanthus in the UK. Bioresour Technol 101(21):8132–8143. doi:10.1016/j.biortech.2010.05.002
3. Mola-Yudego B, Pelkonen P (2008) The effects of policy incentives in the adoption of willow short rotation coppice for bioenergy in Sweden. Energy Policy 36(8):3062–3068. doi:10.1016/j.enpol.2008.03.036
4. Toivonen RM, Tahvanainen LJ (1998) Profitability of willow cultivation for energy production in Finland. Biomass Bioenergy 15(1):27–37. doi:10.1016/S0961-9534(97)10056-3
5. Rosenqvist H, Dawson M (2005) Economics of willow growing in Northern Ireland. Biomass Bioenergy 28(1):7–14. doi:10.1016/j.biombioe.2004.06.001

6. Dimitriou I, Rosenqvist H (2011) Sewage sludge and wastewater fertilisation of Short Rotation Coppice (SRC) for increased bioenergy production—biological and economic potential. Biomass Bioenergy 35(2):835–842. doi:10.1016/j.biombioe.2010.11.010
7. Gonzalez-Garcia S, Mola-Yudego B, Dimitriou J, Aronsson P, Murphy RJ (2012) Environmental assessment of energy production based on long term commercial willow plantations in Sweden. Sci Total Environ 421:210–219. doi:10.1016/j.scitotenv.2012.01.041
8. Gonzalez-Garcia S, Mola-Yudego B, Murphy RJ (2013) Life cycle assessment of potential energy uses for short rotation willow biomass in Sweden. Int J Life Cycle Assess 18(4):783–795. doi:10.1007/s11367-012-0536-2
9. Elowson S (1998) Willow as a vegetation filter for cleaning of polluted drainage water from agricultural land. Biomass Bioenergy 16:281–290. doi:10.1016/S0961-9534(98)00087-7
10. Dimitriou I, Aronsson P (2005) Willows for energy and phytoremediation in Sweden. Unasylva 221(56):46–50
11. Dimitriou I, Mola-Yudego B, Aronsson P (2012) Impact of willow short rotation coppice on water quality. BioEnergy Res 5(3):537–545. doi:10.1007/s12155-012-9211-5
12. Dimitriou I, Mola-Yudego B, Aronsson P, Eriksson J (2012) Changes in organic carbon and trace elements in the soil of willow short-rotation coppice plantations. BioEnergy Res 5(3):563–572. doi:10.1007/s12155-012-9215-1
13. Baum C, Leinweber P, Weih M, Lamersdorf N, Dimitriou I (2009) Effects of short rotation coppice with willows and poplar on soil ecology. Landbauforschung – vTI Agric For Res 3(59):183–196
14. Cannell MG (2003) Carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally, in Europe and the UK. Biomass Bioenergy 24(2):97–116. doi:10.1016/S0961-9534(02)00103-4
15. Heinsoo K, Sild E, Koppel A (2002) Estimation of shoot biomass productivity in Estonian Salix plantations. For Ecol Manag 170(1):67–74. doi:10.1016/S0378-1127(01)00784-8
16. Aylott MJ, Casella E, Tubby I, Street NR, Smith P, Taylor G (2008) Yield and spatial supply of bioenergy poplar and willow short rotation coppice in the UK. New Phytol 178(2):358–370. doi:10.1111/j.1469-8137.2008.02396.x
17. Lindroth A, Båth A (1999) Assessment of regional willow coppice yield in Sweden on basis of water availability. For Ecol Manag 121(1):57–65. doi:10.1016/S0378-1127(98)00556-8
18. Ericsson K, Nilsson LJ (2006) Assessment of the potential biomass supply in Europe using a resource-focused approach. Biomass Bioenergy 30(1):1–15. doi:10.1016/j.biombioe.2005.09.001
19. Tahvanainen L, Rytkönen VM (1999) Biomass production of Salix viminalis in southern Finland and the effect of soil properties and climate conditions on its production and survival. Biomass Bioenergy 16(2):103–117. doi:10.1016/S0961-9534(98)00074-9
20. Mola-Yudego B, Aronsson P (2008) Yield models from commercial willow plantations in Sweden. Biomass Bioenergy 32(9):829–837. doi:10.1016/j.biombioe.2008.01.002
21. Zavitkovski J (1981) Small plots with unplanted plot border can distort data in biomass production studies. Can J For Res 11(1):9–12. doi:10.1139/x81-002
22. Hansen EA (1991) Poplar woody biomass yields. A look to the future. Biomass Bioenergy 1:1–7. doi:10.1016/0961-9534(91)90046-F
23. Searle SY, Malins CJ (2014) Will energy crop yields meet expectations? Biomass Bioenergy 65:3–12. doi:10.1016/j.biombioe.2014.01.001
24. Mola-Yudego B, González-Olabarria JR (2010) Mapping the expansion and distribution of willow plantations for bioenergy in Sweden: lessons to be learned about the spread of energy crops. Biomass Bioenergy 34:442–448. doi:10.1016/j.biombioe.2009.12.008
25. Christersson L (1986) High technology biomass production by Salix clones on sandy soil in southern Sweden. Tree Physiol 2:261–272
26. Christersson L (1987) Biomass production by irrigated and fertilized Salix clones. Biomass 12:83–95
27. Willebrand E, Ledin S, Verwijst T (1993) Willow coppice systems in short rotation forestry: effects of planting spacing, rotation length and clonal composition on biomass production. Biomass Bioenergy 4(5):323–331
28. Verwijst T (1996) Cyclic and progressive changes in short-rotation willow coppice systems. Biomass Bioenergy 11:161–165
29. Alriksson B (1997) Influence of site factors on Salix growth with emphasis on Nitrogen response under different soil conditions. Dissertation, Swedish University of Agricultural Sciences
30. Bergkvist P, Ledin S (1998) Stem biomass yields at different planting designs and spacings in willow coppice systems. Biomass Bioenergy 14(2):149–156. doi:10.1016/S0961-9534(97)10021-6
31. Telenius BF (1998) Assessment of dimensional Relations and Early production in fast-growing decidious tree species. Dissertation, Swedish University of Agricultural Sciences
32. Nordh N (2005) Long Term Changes in Stand Structure and Biomass Production in Short Rotation Willow Coppice. Dissertation, Swedish University of Agricultural Sciences
33. Nordh N, Verwijst T (2004) Above-ground biomass assessments and first cutting cycle production in willow (Salix sp.) coppice—a comparison between destructive and non-destructive methods. Biomass Bioenergy 27:1–8. doi:10.1016/j.biombioe.2003.10.007
34. Weih M, Nordh N (2005) Determinants of biomass production in hybrid willows and prediction of field performance from pot studies. Tree Physiol 25:1197–1206. doi:10.1093/treephys/25.9.1197
35. Linderson ML, Iritz Z, Lindroth A (2007) The effect of water availability on stand-level productivity, transpiration, water use efficiency and radiation use efficiency of field-grown willow clones. Biomass Bioenergy 31:460–468. doi:10.1016/j.biombioe.2007.01.014
36. Adler A, Dimitriou I, Aronssona P, Verwijsta T, Weiha M (2008) Wood fuel quality of two Salix viminalis stands fertilised with sludge, ash and sludge-ash mixtures. Biomass Bioenergy 32:914–925. doi:10.1016/j.biombioe.2008.01.013
37. Aronsson P, Rosenqvist H (2011) Gödslingsrekommendationer för Salix 2011. SLU publication (Swedish). 30 pp
38. Aronsson P, Rosenqvist H, Dimitriou I (2014) Impact of nitrogen fertilization to short-rotation willow coppice plantations grown in Sweden on yield and economy. BioEnergy Res 7(3):993–1001. doi:10.1007/s12155-014-9435-7
39. Spinelli R, Nati C, Magagnotti N (2008) Harvesting short-rotation poplar plantations for biomass production. Croat J For Eng 29(2):129–139
40. Larsson S, Dobrzeniecki P (2004) Agrobränsle AB — the world's leading authority on commercial short rotation willow (*salix*) coppice (SRC) Conference proceedings, Rozwój energii odnawialna na Pomorzu Zachodnim
41. Beringer T, Lucht W, Schapoff S (2011) Bioenergy production potential of global bio-mass plantations under environmental and agricultural constraints. Glob Chang Biol Bioenergy 3:299–312. doi:10.1111/j.1757-1707.2010.01088.x
42. Smeets EMW, Faaij APC, Lewandowski IM, Turkenburg WC (2007) A bottom-up assessment and review of global bio-energy potentials to 2050. Prog Energy Combust Sci 33:56–106. doi:10.1016/j.pecs.2006.08.001
43. Aust C, Schweier J, Brodbeck F, Sauter UH, Becker G, Schnitzler JP (2014) Land availability and potential biomass production with poplar and willow short rotation coppices in Germany. Glob Chang Biol Bioenergy 6(5):521–533. doi:10.1111/gcbb.12083

44. Bentsen N, Felby C (2012) Biomass for energy in the European Union - a review of bioenergy resource assessments. Biotechnol Biofuels 5 (25). doi:10.1186/1754-6834-5-25

45. Mola-Yudego B (2011) Trends and productivity improvements from commercial willow plantations in Sweden during the period 1986–2000. Biomass Bioenergy 35:446–453. doi:10.1016/j.biombioe.2010.09.004