Analysis and Design of a Leek-Celery Intercropping System using Mechanistic and Descriptive Models

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Abstract

Intercropping leek (*Allium porrum* L.) and celery (*Apium graveolens* L.) was recognized as an option to reduce growth and reproductive potential of weeds while maintaining yield and product quality of both crops on a high level. To optimise the intercropping system for yield, quality and weed suppression a combined use of mechanistic and descriptive models, together with experimental work, was applied. An eco-physiological model was used to improve understanding of interplant competition based on physiological, morphological and phenological processes. The model was parameterised based on characteristics of the plants in monocultures and its performance was evaluated for the crop mixtures using experimental data from different growing seasons. After validation the model was used to simulate biomass production and quality of leek, celery and seed production of Common Groundsel (*Senecio vulgaris* L.) for a wide range of crop densities and times of weed emergence. In a second step, the results of the simulations where summarized using a descriptive hyperbolic yield-density model, which then allowed evaluation of the intercropping system in terms of productivity, product quality, and the ability to suppress weeds. The paper will explain this combined modelling approach and how it was used to design and optimise the leek-celery intercropping system. Moreover, this study shows that functional biodiversity, as represented by the intercropping system, can contribute to the improvement of the economical potential while increasing the sustainability of highly developed agricultural production systems.

INTRODUCTION

Many field vegetables such as leek (*Allium porrum* L.) are weak competitors against weeds, causing high costs for labour intensive weed management practices. Recently a number of studies have addressed intercropping as an option for an integrated weed management strategy, particularly in low-external input farming systems (Caporali et al., 1998; Itulya and Aguyoh, 1998; Liebman and Davis, 2000; Rana and Pal, 1999; Schoofs and Entz, 2000). An intercropping system using celery (*Apium graveolens* L.) as a companion cash crop was developed to improve the weed suppression of leek (Baumann et al., 2000). In glasshouse and field experiments it was shown that the increased competition of light by the intercrop canopy compared to a leek monoculture significantly reduced the biomass and the seed production of late-emerging *Senecio vulgaris* L., an important annual weed in vegetable production (Baumann et al., 2001b). However, the strong relative competitive ability of celery in the intercropping system resulted in a loss of leek quality because stem diameter was reduced to < 20 mm (market criterion) (Baumann et al., 2001a). The authors, therefore, concluded that optimization of the intercropping system with respect to crop quality and weed suppression was needed for successful implementation of the intercropping system and suggested the application of eco-physiological simulation models to optimize the system. Earlier, (Kropff and Van Laar, 1993) advocated the use of modeling to develop and optimize weed management systems with respect to cost effectiveness and minimization of environmental effects.

Eco-physiological crop growth models can be very effective to evaluate and develop complex systems, such as multi-species plant communities (Kropff and Van Laar, 1993). Based on physiological, morphological, and phenological processes, such models provide insight into the competitive relationships of the system. These models facilitate the exploration of complex systems without extensive field experimentation to investigate all options in a wide range of conditions. Empirical models and regression techniques can then help to analyze the final outcome of modeling studies and to describe plant interference in cropping systems.

The current study attempts to combine a mechanistic and descriptive modeling approach to optimize the system. A well evaluated eco-physiological model, such as INTERCOM (Kropff and Van Laar, 1993), provides the necessary insight into the processes and plant characteristics determining mutual competitive effects and allows generating a large number of data sets for a wide range of densities and environments. Subsequent application of a statistical descriptive model to the generated data sets can help to summarize the results, to calculate the relative competitive ability of the system components, and to describe yield and product quality of the component crops in relation to plant density and mixing ratios.

The objective of this study was to evaluate the use of combined modeling approaches for analysis and design of a leek and celery intercropping system with the main aim of optimizing this system in respect to yield and quality, while improving weed suppression.

MATERIALS AND METHODS

An adapted version of the eco-physiological competition model INTERCOM (Kropff and Van Laar, 1993) was used to simulate interplant competition between leek, celery and *S. vulgaris* in pure and mixed stands for various conditions and a wide range of crop densities and different relative times of weed emergence. The model was simplified with respect to physiological processes but included the original detailed simulation of competition for light (Baumann et al., 2002). Because water and nutrients were available in ample supply in the experimental system, competition for these resources was not simulated in this version of the model. The competition model was parameterized using experimental data from pure stands of the crops. Validation with independent data showed that the model simulated growth in both monocultures and mixtures accurately. For a detailed description of the model, the eco-physiological characteristics of the crops and the underlying experiments the authors refer to (Baumann et al., 2002). To study the growth of *S. vulgaris* and its effect on intercrop performance, the model was extended to include this weed species. Parameter values were derived from field experiments (Baumann et al., 2002) and additionally from earlier studies carried out by (Schnieders, 1999). The model was validated with independent data from monocultures and mixtures of the three species collected in two field experiments, carried out in 1997 and 1998 (Baumann et al., 2001b).

Simulation Studies

After validation of the model, the performance of pure and mixed crop stands with and without *S. vulgaris* was simulated for local environmental conditions. Plant density for leek was varied between 0 to 25 plants m^{-2}, and plant density of celery was varied between 0 and 20 plants m^{-2}. Plant density of *S. vulgaris* remained constant at 50 plants m^{-2} at a relative emergence time of 0, 10, 20, 30 and 40 d after crop establishment. Simulation runs were conducted with weather data of 1997 and 1998 from Wädenswil, Switzerland for all combinations of crop densities with and without *S. vulgaris*. Biomass production and per-plant mass of the species after a growing period of 88 for 1997 and 92 d for 1998, were output of the model. For leek, the diameter of the pseudostem, which is used as a quality parameter, was calculated based on the per-plant mass, because a high correlation (r^2=0.92) between the dry mass of above-ground organs and pseudostem diameter had been found in earlier experiments (Baumann et al., 2002). For celery, the per-plant fresh mass was calculated based on an average dry matter content of 7.3%, which was found in experiment I and II, and did not differ significantly between the various treatments. For *S. vulgaris*, seed production was estimated based on the established linear relationship between per-plant dry mass and number of seeds per plant (Baumann et al., 2001b; Schnieders, 1999).

Data Analysis

The relative competitive ability of the crops was analyzed using an approach proposed by (Spitters, 1983; Watkinson, 1981; Wright, 1981). This approach is based on the notion that the biomass-plant density response can be described by a rectangular hyperbola (De Wit, 1960; Spitters, 1983). The model relates the biomass of each species to the density of the other species in the mixture and can be calculated by:

$$Y_{L,C,S} = \frac{N_L}{b_{L,0} + b_{L,L} N_L + b_{L,C} N_C + b_{L,S} N_S} \qquad [1]$$

where $Y_{L,C,S}$ is the yield of leek (L) in presence of celery (C) and *S. vulgaris* (S) (g m^{-2}), N_L, N_C and N_S are the plant densities (plants m^{-2}) of three species, $b_{L,0}$ is the intercept denoting the reciprocal of the virtual biomass of an isolated leek plant (plant g^{-1}), and $b_{L,L}$, $b_{L,C}$ and $b_{L,S}$ (m^2 g^{-1}) are parameters for intra- and interspecific competition, respectively. Similarly, the yield of celery *S. vulgaris* in presence of the other two species could be calculated. Dividing yield by plant density of corresponding species result in the per-plant mass, which was used to derive crop quality parameters and seed production for *S. vulgaris*.

Optimization

To optimize the intercropping system, crop mixtures with either the same quality, the same yield, or a similar weed suppressive ability were determined by calculating isolines for these parameters. For this purpose, Eq. [1] was rewritten to obtain an expression for plant density of celery (N_C). Isolines with equal biomass production of each of the components of the mixture were then determined by taking a specific crop yield (Y) and calculating the corresponding celery density (N_C) for a range of leek densities. To calculate isolines for mixtures with similar quality, quality parameters for leek and celery, and seed production for *S. vulgaris* were first converted into per-plant dry mass. Consequently a similar procedure as described for yield isolines was followed for per-plant dry mass isolines.

Isolines for total biomass production of the intercrop were calculated by first adding the terms of equation [1] for the biomass production of leek and celery, after which the combined equation could be rewritten to obtain an equation for N_C. Accordingly, the total financial yield, Y_T, of the mixture was calculated as:

$$Y_T = \frac{P_L N_L}{b_{L,0} + b_{L,L} N_L + b_{L,C} N_C} + \frac{P_C N_C}{b_{C,0} + b_{C,C} N_C + b_{C,L} N_L} \qquad [2]$$

where P is the price of the product received by the farmer (€ kg^{-1}), the other parameters are defined as indicated for Eq. [1] and the suffixes L and C are for leek and celery, respectively. Rewriting Eq. [2] for N_C, which results in a quadratic equation, allowed calculation of isolines for crop stands with equal financial yield. For the calculation, average prices achieved by farmers over a five year period between 1993 and 1998 where used (Spigt and Janssen, 1997). The crop stand with the highest financial gross return was detected by determining the intersection of the Y_T-isoline and the minimum quality isoline for leek. This was established by introducing the equation for the minimum quality isoline into the equation of the Y_T-isoline. Calculating the celery density for which the first derivative, with respect to financial yield, of this combined equation equals zero made it possible to determine the crop densities of the mixture with the highest financial yield. The sensitivity of the yield and crop densities to a 5% change of the prices was tested.

RESULTS

Model Performance

The model was calibrated based on data from monocultures of the crops grown in field experiments carried out in 1996 and 1998 (Baumann et al., 2002). Calibration for *S. vulgaris* was based on experimental data from monocultures of the weed in Exp. II (1998) and from literature (Schnieders, 1999). For the model evaluation, independent data sets from mixed stand treatments of Exp. I and II were used. Dry matter production was simulated accurately for leek monoculture and mixture in 1997 and 1998 (Fig. 1A). For celery, simulations with 1998 weather data underestimated the observed biomass production in the mixed stand compared to observed data in experiment II (Fig. 1B). For the mixture in experiment I and celery pure stands of both years simulation of celery production was acceptable. Standard errors for celery dry matter production in the experiments were high in both years. The model simulated *S. vulgaris* biomass in all crop stands very accurately (Fig. 2) for 1998. Biomass of *S. vulgaris* was more reduced in all crop stands when the plants emerged later than the crop. Biomass was more reduced in the crop mixture and celery monoculture compared to leek monoculture particularly for early dates of emergence.

Isolines for Crop Quality,Yield, and Weed Biomass

Isolines for crop stands with equal quality were calculated using the hyperbolic competition model which was fitted to the simulated data for leek (Fig. 3A) and celery (Fig. 3B). For leek, the diameter of the pseudostem was used as a quality parameter; and isolines for diameters ranging between 15 and 30 mm were calculated. A minimum pseudostem diameter of 20 mm is required for marketable leek plants in many European countries (Brewster, 1994). For celery, isolines for the per-plant fresh mass are given. Market requirements range between 0.25 kg and 1 kg or more, larger plants being used for industrial processing.

A second set of isolines indicates crop stands with equal yield levels for leek (Fig. 3C) and celery (Fig. 3D). For both crops, the slopes of the isolines differed six-fold if the yield level was tripled. In combining isolines for yield with the isoline for an acceptable leek quality, a solution space indicating crop stands with acceptable quality and high yields could be determined. Isolines for crop stands with equal total yield could be drawn by adding leek and celery yield (Fig. 4A). The highest biomass production was achieved with celery monocultures.

Financial rather than physical yield determines solutions with the highest economic value. Isolines for total financial yield were calculated using Eq. [2] and average prices of 0.35 € kg^{-1} and 0.19 € kg^{-1} for leek and celery, respectively. By combining isolines for financial yield with the quality isoline for leek, the mixture with the highest financial yield could be determined (Fig. 4B). With a crop mixture of 9.4 celery and 19 leek plants m^{-2}, indicated by the point where the isoline for financial yield touches the leek quality isoline, a financial yield of 27854 € could be achieved. This yield was 7% higher than the maximum financial yield that could have been achieved with a leek monoculture and 9% higher than a maximum financial yield of a celery monoculture with a per-plant fresh mass of 730 g which is equal to the per-plant fresh mass achieved in the optimum intercrop. Increasing the price for either leek or celery by 5% while keeping the price of the other crop constant resulted in a 2.5% and 3% increase of the financial yield for leek and celery, respectively. Decreasing the prices in the same way by 5% caused a financial yield reduction of 2% and 2.6% for leek and celery, respectively. The optimal leek and celery density was more sensitive to altering the leek price than to altering the celery price.

The effect of the cropping system on the reproductive potential of 50 *S. vulgaris* plants m^{-2}, which were introduced 40 d after crop establishment, is shown by the isolines with equal production of *S. vulgaris* seeds m^{-2} in Fig 4C. The slope of the curves reflects the five to six times higher sensitivity of *S. vulgaris* to competition by celery compared to leek. To reduce the seed production of 50 initial *S. vulgaris* plants m^{-2} from 500 to 250 seeds m^{-2}, a 2.7 times increase of plant densities was required in the crop stands. A similar effect was achieved when, for a given crop stand, the initial *S. vulgaris* density was reduced from 50 to 18.5 plants m^{-2}. Seed production of *S. vulgaris* emerging 30 instead of 40 days after crop establishment was about 5.6 times higher. Hence, the extension of the weed free period from 30 to 40 d reduced the seed production of *S. vulgaris* by 82%.

Combining isolines for financial yield, leek quality, and *S. vulgaris* seed production created a solution space including crop mixtures with high yield level, quality production and high suppressive ability for *S. vulgaris* (Fig. 4D). The maximum financial yield did not coincide with highest suppressive ability. The latter could be further increased with increasing numbers of celery in the mixture, which, however, will cause a dramatic reduction of financial yield as quality criteria for leek will not be met anymore. Seed production of *S. vulgaris* could be reduced by 38% by growing a celery monoculture at density of 25 plants m^{-2} which would produce plants with a per-plant fresh mass of about 500 g and result in the same financial return as the highest yielding crop mixture. The highest yielding leek monoculture, on the other hand, resulted not only in an 7% lower financial return than the highest yielding mixture, it also caused a *S. vulgaris* seed production, which was 35% higher (Fig. 4D). Similar comparisons could be made for yield, quality and levels of weed suppression between other crops stands.

DISCUSSION

Modelling Weed Growth in Monocultures and Intercropping Systems

Calibration of the model INTERCOM for two crops and one weed species demonstrated a large increase in complexity of interplant competitive relations when numbers of species considered is increased form two to three. Morphological characteristics such as plant height, and leaf area dynamics, which in the weed-free crop mixture proved to be determinant for competition (Baumann et al., 2002), were also critical for the simulation of weed suppression. Adaptations to the model had to be made with respect to early leaf area development, which is often temperature determined (Horie et al., 1979).

The model underestimated the biomass production of celery in the crop mixture in 1998 (Fig. 1B) whereas the two other species were simulated accurately. This was possibly the result of a different response of the leaf morphology (e.g., higher *SLA*) of celery if grown in mixture compared to monoculture. The model, parameterized for monoculture, was not able to account for these adaptations occurring in the mixture. Model performance was considered acceptable because the effect of *S. vulgaris* on the crops (Fig. 1) and inversely the effect of the crops on *S. vulgaris* (Fig. 2) was simulated correctly for the other crop stands in both years.

Optimization of the Intercropping System

Insight into the competitive relations between crops and weed enabled the optimization of the system with respect to financial yield and weed suppression. Crop quality plays a predominant role, as it is critical for the profitability of the system. For leek and celery there is a strong response of quality parameters to intra- and interspecific competition (Baumann et al., 2001a). For celery, quality requirements depend on whether the produce is used for industrial processing, convenience food or the fresh market. Leek pseudostem diameter proved to be the limiting factor for crop quality in the intercropping system. Therefore, crop mixtures represented by the isoline for leek plants with a pseudostem diameter of 20 mm delimit the solution space for profitable mixed stands (Fig 3 and 4).

Although high biomass yields can be achieved with high proportions of celery in the mixture (Fig. 4A), producing leek is more profitable because its price is higher than that of celery. A large yield gap was found between the calculated maximum financial yield and the yield level obtained with plant densities as used in practice, where lower densities are usually planted to ensure high plant quality and to enable efficient and labor-saving cultivation and harvesting. In particular, leek is generally grown at row distances between 0.5 and 0.75 m. For high plant densities (e.g. >30 plants m^{-2}), in-row spacing would need to be between 4 and 6 cm, which would increase the plant-to-plant variability and would result in a higher proportion of undersized plants (Brewster, 1994). Therefore, limitations for the spatial arrangement of the crop directed by the cultivation practices, as well as the use of below optimal densities that meet the risk perception of the farmer, have to be taken into account.

Depending on whether the intercropping system is compared with a monoculture production of leek or celery, a double advantage or a trade-off between financial yield and weed suppression arises. For leek production, the yield advantage of an intercropping system is combined with a reduction of *S. vulgaris* seed production. If celery production is considered, a monoculture with the same yield as a mixture suppresses *S. vulgaris* better (Fig 4D). In this study, leek was the crop of interest, due to its economic potential in many European countries and the weak competitive ability against weeds. It was shown that high quality leek can be produced at a high yield level in an intercropping system with celery, which at the same time has distinct advantages with respect to the suppression of weeds.

CONCLUSIONS

A combined approach using mechanistic and statistical descriptive models for analyses and optimization of an intercropping system of leek and celery proved to be very effective. With a new version of the model INTERCOM, biomass production, product quality and weed seed production for monocultures and mixtures could accurately be simulated. Application of a descriptive regression model for summarizing the simulation results was very effective and facilitated optimization of the intercropping system. It is concluded that this combined modeling approach enlarges the potential of mechanistic crop growth and competition modeling to be used in the optimization and design of cropping systems.

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Figures

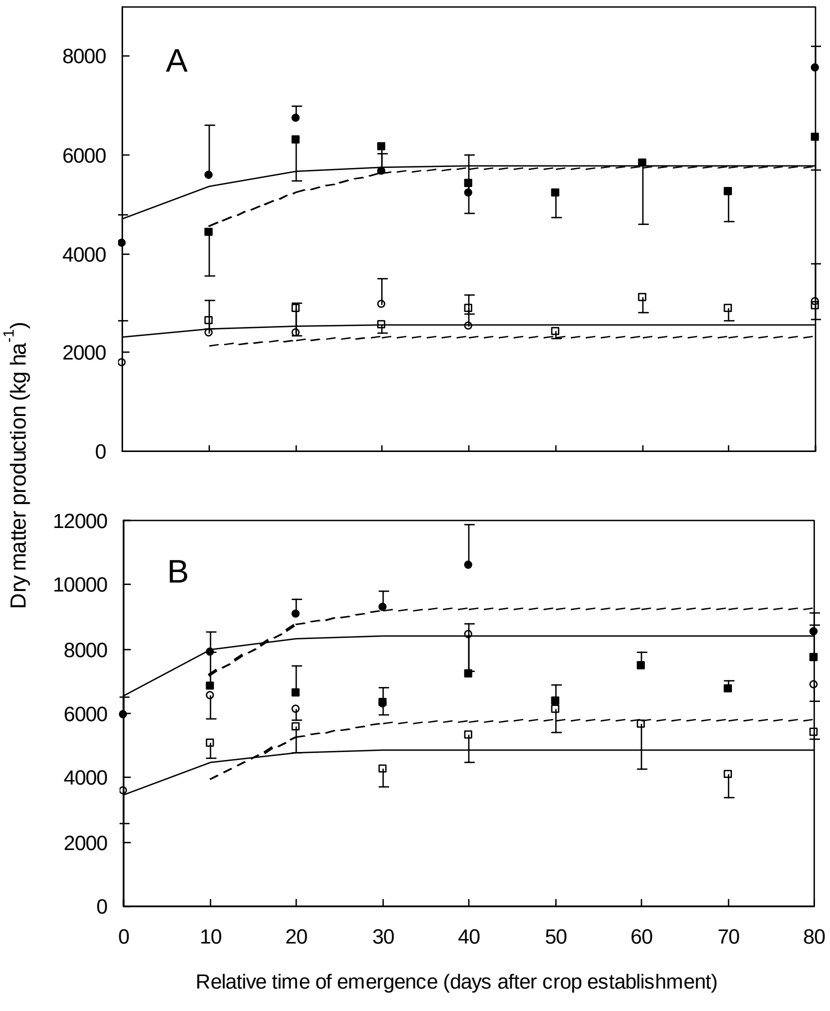

Fig. 1. Measured (symbols) and simulated (lines) shoot dry matter of leek (**A**) and celery (**B**) at harvest in monoculture (filled symbols) and mixture (open symbols) as affected by the relative time of emergence of *Senecio vulgaris*. Results of 1997 (Exp. I; squares; dashed lines) and 1998 (Exp. II; circles; solid lines). Error bars are standard errors of means.

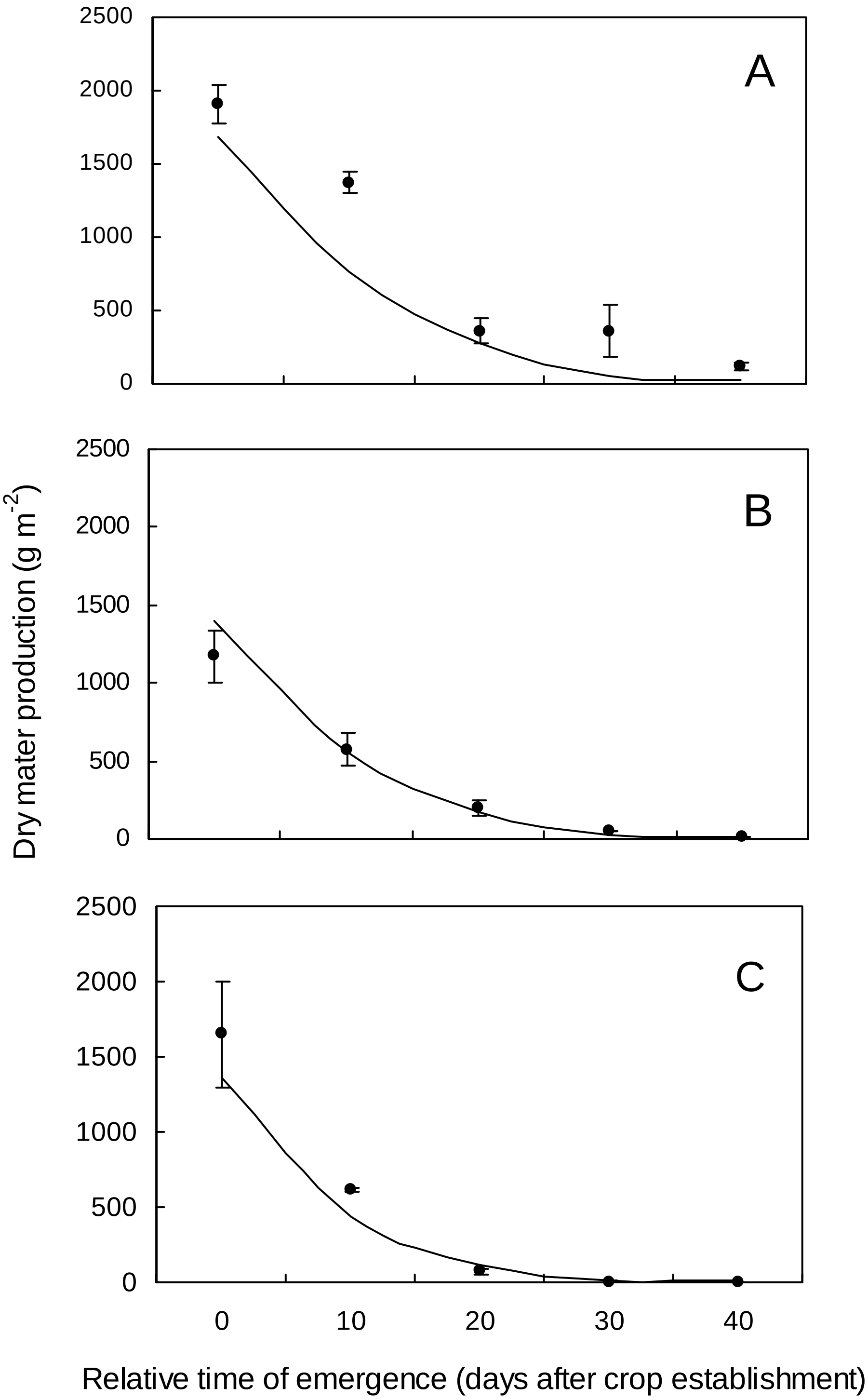

Fig. 2. Measured (symbols) and simulated (lines) shoot dry matter of *Senecio vulgaris* grown in leek monoculture (**A**), leek-celery intercrop (**B**), and celery monoculture (**C**) as affected by the relative time of emergence. Error bars are standard errors of means.

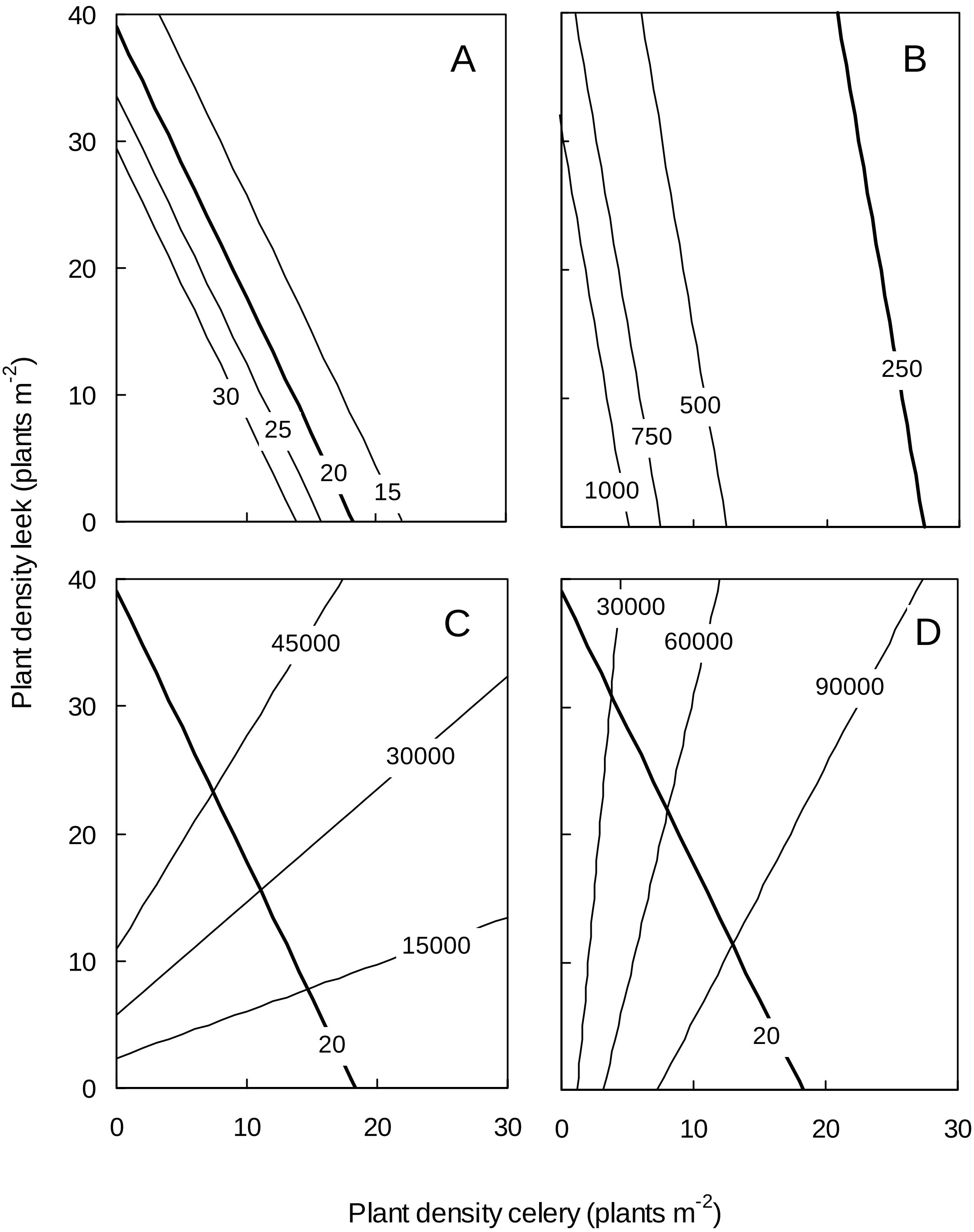

Fig. 3. Isolines for crop stands producing (**A**) leek with similar pseudostem diameters (mm); (**B**) celery with similar per-plant fresh mass (g); (**C**) similar leek yield (kg fresh mass ha^{-1}); and (**D**) similar celery yield (kg fresh mass ha^{-1}). In compound figures **C** and **D** the quality isoline for leek given by a minimum pseudostem diameter of 20 mm is included.

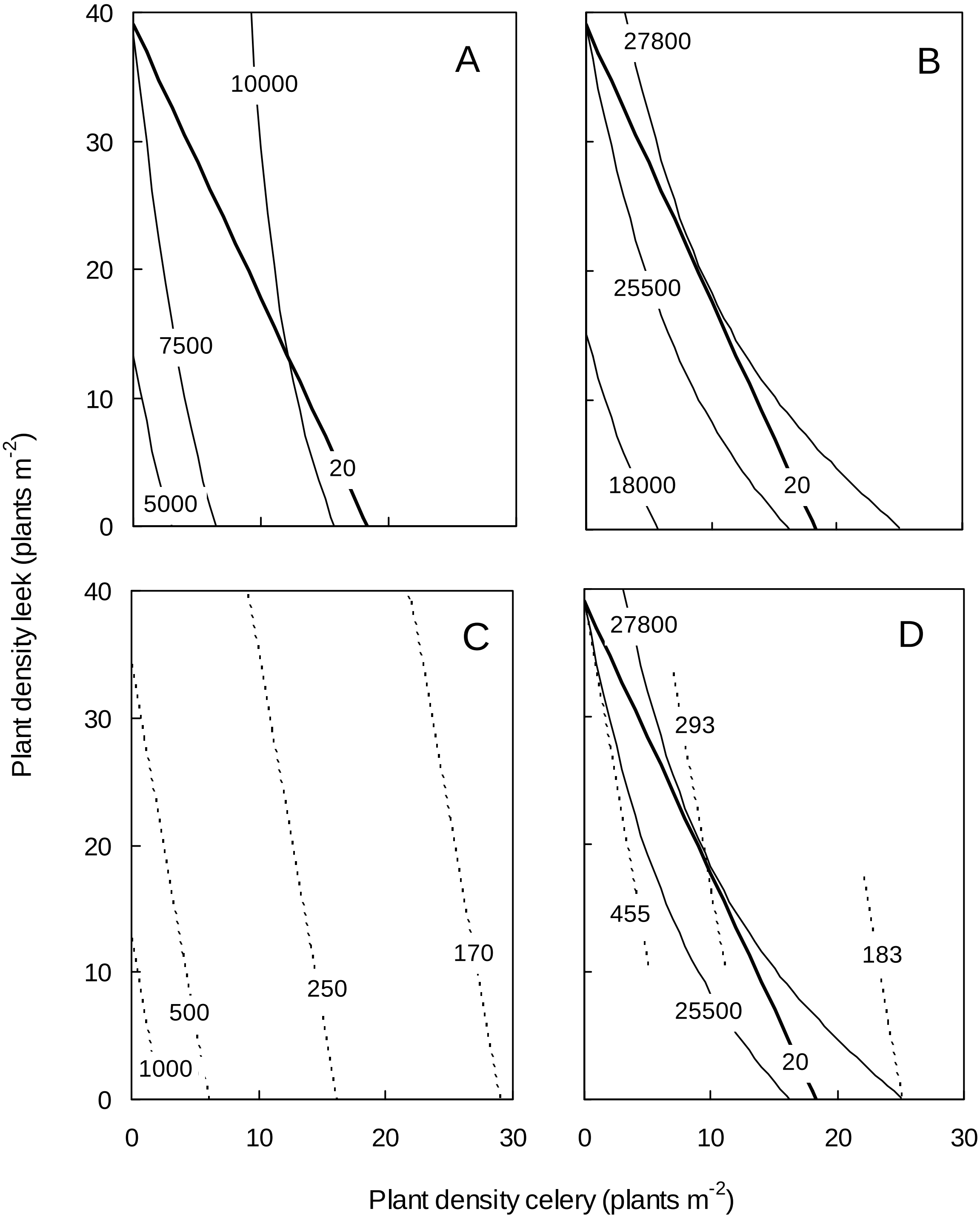

Fig. 4. Isolines for crop stands with (**A**) similar total biomass production (kg dry matter ha^{-1}); (**B**) similar total financial yield (€ ha^{-1}); and (**C**) similar seed production by initially 50 *Senecio vulgaris* plants m^{-2} (seeds m^{-2}). Compound figure (**D**) combines isolines for financial yield, minimum required leek pseudostem diameter, and seed production of *S. vulgaris*. The isoline for minimum required leek pseudostem diameter of 20 mm is also included in compound figure **A** and **B**.