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New Approaches to Organic Blueberry (*Vaccinium corymbosum* L.) Production in Alkaline Field Soils

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Summary

Production of *Vaccinium corymbosum* L. is limited to acidic soils with high organic matter content. This specific soil requirement is limiting the possibilities to cultivate *V. corymbosum* L. in many regions of Central Europe. The aim of this study was to overcome the limiting production factors occurring under the soil and climate conditions of Switzerland: (1) evaluation of natural growing substrates without peat as required for organic production; (2) adjustment of the optimal pH in the growing substrate; (3) regulation of water issues (water quality and mulching) and (4) development of a suited planting system.

Pine sawdust was evaluated to be the best alternative growing substrate compared to peat moss. Optimal pH adjustment in pine sawdust substrate was found to be 3.8 ($CaCl_2$) and 4.2 (H_2O). In field cultivation, an amount of 30 g S $year^{-1}$ $plant^{-1}$ to lower the pH of the pine sawdust ditches was sufficient for good plant and yield development. This acidification resulted in better growth (+48 %) and higher yield (+55 %) when alkaline ground water (357 mg L^{-1} $CaC0_3$) was used for irrigation. Acidification with citric acid gave poor results. A mulch of pine bark on the sawdust ridge increased growth by 59 % and yield by 25 %.The newly developed flat ditch system with low sawdust ditches buried partly into the ground was as suitable as the standard planting system with deep ditches lined with plastic film. By integration and application of these new findings, a system for commercial organic blueberry production under Swiss conditions and on alkaline soils was developed.

Key words. bark – citric acid – mulch – pH – sawdust – substrate – sulphur

Introduction

Highbush blueberry *Vaccinium corymbosum* L. is an interesting crop for organic production because of its good pest and disease tolerance under Central European conditions. In addition, it is a high-value crop. However, at the beginning of our experiments an organic upper-land blueberry production was considered to be unrealistic because of too many unsolved key problems like the lack of an alternative to peat substrate, which is not allowed for organic production, no precise method for substrate acidification, no suitable cultivation system, no possibility for adequate N-fertilization. The aim of our study was to develop a complete, well working production system for organic blueberry production. The way we chose to find the solutions was a "puzzle" approach: In a first phase we carried out several parallel studies to develop and optimize single critical factors. Finally we combined and tested the most promising strategies into systems that are close to commercial production.

It is known since many years that *V. corymbosum* L. cannot thrive in soils having of neutral or alkaline reaction (Coville 1910). Harmer (1944) described the optimum soil pH for *V. corymbosum* L. production to lie between 4.0 and 5.2. In contrast Stene (1939) supposed that blueberries do not require a distinctly acid soil as long as plant nutrients are present in adequate amounts. However, most studies and experiences confirm negative effects of neutral or alkaline soils on the development of blueberries. The restriction to acidic soils with pH below 5.2 is limiting the possibilities to cultivate *V. corymbosum* L. in many regions of Central Europe, including Switzerland. Cummings et al. (1981) showed for *V. ashei* Reade that sawdust could neutralize the harmful effects of an initially high soil pH. According to Odneal and Kaps (1990) fresh or aged pine bark can substitute sphagnum peat as a soil amendment to cultivate *V. corymbosum* L. in the upland mineral soils of Missouri. Further they suggest pine bark as an economic amendment for general soil improvement, particularly to improve soil aeration of heavier soils showing *Phytophthora* root disease problems. Peterson et al. (1987) described also a positive effect of soils amended with hardwood sawdust and sulphur on growth of *V. ashei* Reade. Baily (1941) stated that optimal soil pH for blueberry is depending on soil character: With fine sandy loam he noticed best growth at pH 5.2. However, in a mixture of the same soil with peat best growth was obtained at pH 4.8. Thus, the recommended soil pH levels are not mandatory for the pH adjustment of growing substrates.

Irrigation water quality (low electrical conductivity, low Na^+, Ca^{2+} and content of other cations) is also an important factor in blueberry (*V. ashei* Reade) production (Spiers and Braswell 1992). According to Haby et al.

(1986) growth of *V. ashei* Reade increased if plants were irrigated with rainwater (0.0150 dSm^{-1} EC) or surface pond water (0.155 dSm^{-1} EC) compared to plants irrigated with deep well water. From irrigation with deep well water resulted an increase of soil pH, which lead to an increased leaf content of Na and decreased leaf content of Ca and Mn. HANSON and STEIN (1999) observed that the chemical characteristics of water can greatly affect the pH of sand soils. They experienced that alkaline pond water (148 mg L^{-1} $CaCO_3$) prior acidified with H_2SO_4 may reduce the pH of neutral sand soil, making them more suited for cranberry (*V. macrocarpon* Ait.) production.

Several authors (HAYNES and SWIFT 1986; GAGNON et al. 2003) experienced an increase in plant development of *Vaccinium* if the soil or the substrate was covered with mulch. To grow *V. corymbosum* L. in alkaline field soils COVILLE (1910) suggested to plant in trenches or holes of at least 30 cm depth filled with well-rotted peat, and to mulch the surface thickly either with leaves or clean sand. Meanwhile numerous studies were conducted to develop suitable cropping systems and pH-regulation for such conditions. KOBEL (1976) experienced that in Swiss blueberry production on upper land and a soil pH of 7.2 is possible if peat and wood shavings are added into the root-zone. However, the Swiss regulations for organic production (BIO-SUISSE 2006) do not allow the use of peat as a substrate for production plants because peat is a non renewable resource, and its mining is combined with the destruction of marshland eco systems. Therefore, alternative cropping systems are needed for blueberry-production on upper land.

The aim of this study was to overcome the limiting factors occurring under the soil and climate conditions of Switzerland: (1) evaluation of natural growing substrates without peat; (2) adjustment of the optimal pH in the growing substrate; (3) regulation of water issues (water quality and mulching); and (4) development of a suitable planting system.

Material and Methods

Pot-Experiment 1: Substrate testing

Different substrates for blueberry-production were tested in this experiment without any acidification measures in order to find an alternative to peat. Tested substrates were: oak bark; oak sawdust; 50 Vol.-% oak bark + 50 Vol.-% oak sawdust; beech bark; beech sawdust; 50 Vol.-% beech bark + 50 Vol.-% beech sawdust; pine bark; pine sawdust; 50 Vol.-% pine bark + 50 Vol.-% pine sawdust; peat 'Floragard'; and garden soil from Frick with 54 % clay, 28 % silt, 14 % sand, 4 % organic matter, pH (H_2O) 7.5.

The experiment was carried out from 1998 to 2002 at the Research Institute of Organic Agriculture at Frick (Geographical coordinates: 47 ° 30 ' 58.58 N, 8 ° 01 ' 34.39 E; altitude: 350 m above sea level; annual rainfall: 979 mm; average annual air temperature: 8.4 °C; average annual global radiation: 126 W m^{-2}).

V. corymbosum L. 'Bluecrop' were obtained as rooted cuttings on April 27, 1998 and yearlong sets (October 01, 1998; October 15, 1999). Substrates were not removed before planting.

The tested substrates (sawdust and bark in fresh condition) were filled in 6-liter pots. The six replications (6 x 1 pots per treatment) were divided in two blocks. The pots were placed outdoors on a rack area covered with a water permeable plastic film.

Pots were fertilized with "Biorga N-liquid 9.0 % N", a molasse product. Total input of nitrogen (N) applied during the whole testing period (1998–2002) was 2.2 g L^{-1} substrate. Irrigation was conducted by sprinkle irrigation (water hardiness: 20 °dH, 36 °fH corresponding to 357 mg L^{-1} calcium carbonate, $CaCO_3$). Each autumn before leaves turned to red pH (H_2O) of the substrate was measured in a 2:1 (volumetric) water: substrate suspension, with a glass electrode.

Plant biomass (fresh weight) was determined by cutting all one season-old tips on 1 cm long snaps above the older wood every autumn. Volume shrinkage of the substrates due to compacting and degradation was evaluated each year by measuring the difference between the original height of soil surface marked on the pots and height of soil surface in the following autumn. After measurement shrinkage was compensated every year by adding fresh substrate at the bottom of the pots. For statistical analysis cumulated shrinkage (in cm) over the 4 years was used. Simultaneously substrates were checked for larvae of *Trichius fasciatus* L. which were killed after being counted.

Pot-Experiment 2: Optimal pH in the pine sawdust

The aim of the second pot-experiment was the determination of the optimal pH level in a peat-free substrate (pine sawdust).

On March 17, 2003 fresh pine sawdust (pH (H_2O): 5.0) was mixed with fertilizer (980 mg N L^{-1} substrate: 30 % horn meal (14 % N) and 70 % horn chips (14 % N)) and filled in 6-liter pots. On March 27, 2003 sulphur (S) and $CaCO_3$ was added to the 1 cm layer (0.5 L pot^{-1}) of chopped pine bark (size 0–10 mm) to achieve different pH levels. We used S (content 99.9 %) and $CaCO_3$ (content 90.0 %) in the following dosages: 5 g S; 4 g S; 3 g S; 2 g S; 1 g S; 5 g S + 19.29 g $CaCO_3$ (5 g of S neutralize 19.29 g $CaCO_3$); 3.86 g $CaCO_3$; 7.72 g $CaCO_3$; 11.57 g $CaCO_3$; 15.43 g $CaCO_3$; 19.29 g $CaCO_3$; 23.15 g $CaCO_3$; 27.01 g $CaCO_3$; 30.86 g $CaCO_3$. One treatment with pine bark without S and $CaCO_3$ and one treatment without bark were installed.

On April 27, 2003 yearlong sets of 'Bluecrop' were planted. The six replicates (6 x 1 pot $treatment^{-1}$) were divided in 3 blocks. Pots were fertilized with 200 mg N L^{-1} substrate ("Biorga N-liquid 9.0 % N") on 15 May, 2003. Irrigation was conducted by sprinkle irrigation (water quality see above) with a total amount of 6.4 L pot^{-1} in 2003.

On September 03, 2003, before leaves turned to red pH (H_2O) of the substrate was measured in a 2:1 (volumetric) water: substrate suspension, with a glass electrode. At the same date, the pH ($CaCl_2$) was measured using 2.5:1 (volumetric) 0.01 M $CaCl_2$-solution: substrate suspension with a glass electrode. As an indicator for plant vitality the content of chlorophyll in leaves was assessed on 3 to 25 leaves per sample with the SPAD-method ("Minolta SPAD-502"). We assumed that optimal pH adjustment of the pine-sawdust sample is where SPAD-values (chlorophyll-index) are highest.

Field-experiment 1: Irrigation water quality and bark mulching

The aim of the first field experiment was to evaluate the influence of irrigation water quality and bark mulching on substrate pH level, plant volume and blueberry yield. The experiment was carried out from 2000 to 2005 at Frick on an arable field of loamy clay soil (54 % clay, 28 % silt, 14 % sand, 4 % organic matter, pH (H_2O) 7.5).

On February 24, 2000 raised beds were formed with fresh pine sawdust (Fig. 1). On February 28 two-yearlong sets 'Bluecrop' were planted at distances of 1.5 m between rows and 0.85 m within rows.

The following treatments were established: control without irrigation; irrigation with hard water (20 °dH, 36 °fH water hardiness corresponding to 357 mg L^{-1} $CaCO_3$); hard water and S (details see below); soft water (5 °dH, 9 °fH water hardiness corresponding to 89 mg L^{-1} $CaCO_3$, rainwater (0 °dH, 0 °fH water hardiness). The following amounts of water were given: 26 L $plant^{-1}$ in 2000; 25 L in 2001; 169 L in 2002; 93 L of hard water, 103 L of soft water and 113 L of rain water in 2003; 330 L in 2004. This summed up to a total amount (2000–2005) of 643 L $plant^{-1}$ (hard water), 653 L $plant^{-1}$ (soft water) and 663 L $plant^{-1}$ (rain water), respectively. Therewith the input of $CaCO_3/MgCO_3$ and NaCl by irrigation was 230 g $CaCO_3/MgCO_3$ for the hard water irrigated treatments and 58 g $CaCO_3/MgCO_3$ and 100 g NaCl for the soft water irrigated treatment. Sub treatments with or without bark mulching were applied to each main treatment. Each treatment combination was established in 2 blocks (4 plants per plot with 2 plants for measurements). Plots were fertilized with 30 g N $plant^{-1}$ ("Biorga Quick" 10 % N, 1 % K_2O) in 2000, 15 g N $plant^{-1}$ ("Biorga N-liquid" 9.0 % N) in 2001, 20 g N $plant^{-1}$ ("Biorga Quick") in 2002, 15 g N $plant^{-1}$ ("Biorga N-liquid") in 2003, 15 g N $plant^{-1}$ ("Biorga Quick") in 2004, and 15 g N $plant^{-1}$ ("Biorga Quick") in 2005. Acidification in treatment hard water treatment with S was done by applications of S (content: 99.9 % S) on the substrate: 20 g $plant^{-1}$ on February 29, 2000, 50 g $plant^{-1}$ on October 19, 2001, 30 g $plant^{-1}$ on May 28, 2003, and 40 g $plant^{-1}$ on April 14, 2005 (total 2000–2005: 140 g $plant^{-1}$).

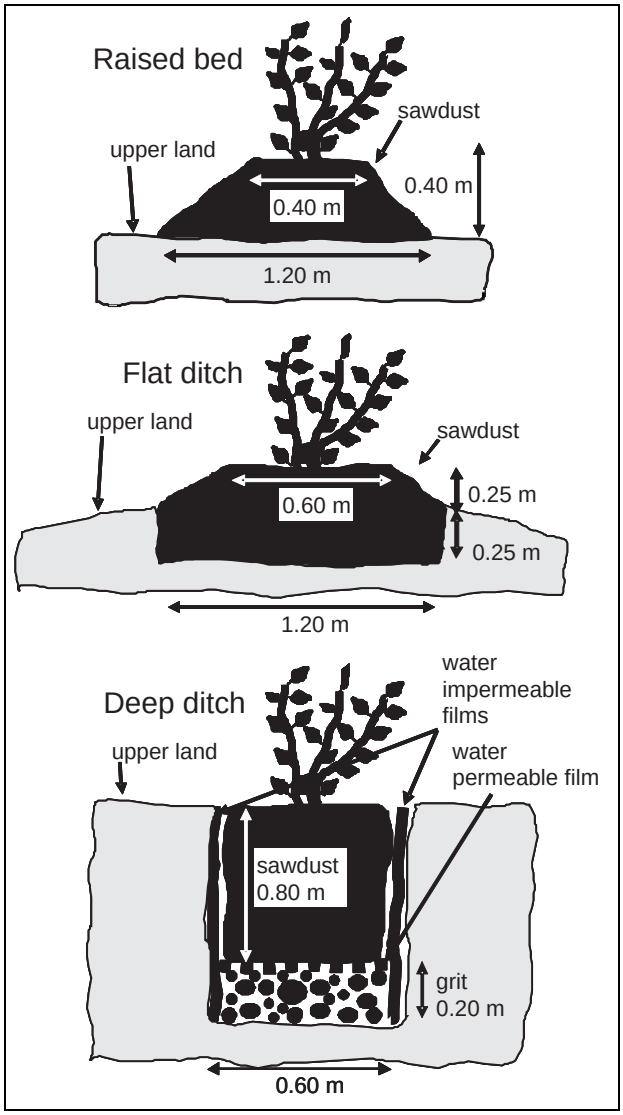


Fig. 1. Cultivation systems in field-experiment 2: Raised bed, flat ditch and deep ditch.

In September before leaves turned red pH (H_2O) of the substrate was determined (in 2 :1 water : substrate suspension with a glass electrode). Yield was evaluated by weighting fruits of each shrub. Shrub volume was measured after leave fall (formula: plant height*radius at medium plant height^2*π).

Field-experiment 2: Cultivation system and pH-regulation

The aim of the second field experiment was to evaluate the different systems and strategies of pH regulation under conditions close to commercial production. The experiment was carried out from 1998 to 2005 at Frick on an arable field of loamy clay. We tested 3 cultivation systems: raised bed, deep ditch (standard method), flat ditch (Fig. 1). Each cultivation system was established in 2 rows of 72 m length. To establish the raised beds the field was weeded thoroughly with rotor-tillage. Per running meter 320 L of pine sawdust were used. The deep ditch was built by digger. Per running meter 120 L of grit, 480 L of pine sawdust, 0.6 m^2 of water permeable film, and 2.0 m^2 of water impermeable film were used. The flat ditch was built by plough. Per running meter 525 L of pine sawdust were used.

In each cultivation system two different acidification methods were tested: S and citric acid, with a total input of S (99.9 % S content) of 240 g $plant^{-1}$ (30 g $year^{-1}$; 1998–2005) and a total input of citric acid of 1048 g $plant^{-1}$ (131 g $year^{-1}$; 1998–2005). Consequently both sub-treatments were equal concerning the acid-equivalents. The control was untreated. Each sub-treatment was established with 3 replicates per row with 8 plants per replicate (4 'Bluecrop' and 4 'Reka').

Two-yearlong sets, 'Bluecrop' and 'Reka' were planted on September 29, 1998 planted at distances of 3.00 m between rows and 1.00 m within rows.

Each treatment combination was present in six repetitions, divided in three blocks (four plants per repetition of which two plants for measurements).

Irrigation was conducted by sprinkle irrigation (water hardiness: 20 ° dH, 36 ° fH correspond to 357 mg L^{-1} $CaCO_3$). Fertilization was followed as described in Table 1. The shrinkage of the sawdust substrate, caused

Table 1. Fertilisation in field-experiment 2.

Date	Fertilization	Total nutrient input (plant^{-1})
October 08, 1998	"Biorga Quick" (10 % N, 1 % K_2O)	6 g N
	"Hypophosphate" (29 % P_2O_5)	6 g P_2O_5
	"Kalimagnesia" (29 % K_2O, 6 % Mg)	15 g K_2O, 3 g Mg
March 30, 1999	"Biorga Quick" (10 % N, 1 % K_2O)	12 g N
	"Hypophosphate" (29 % P_2O_5)	6 g P_2O_5
	"Kalimagnesia" (29 % K_2O, 6 % Mg)	15 g K_2O, 3 g Mg
June 02, June 17 and July 09, 1999	"Biorga N-liquid" (9.0 % N)	
April 30, 2000	"Biorga Quick" (10 % N, 1 % K_2O)	8 g N
June 19 and July 28, 2000	"Biorga N-liquid" (9.0 % N)	
May 11, May 30, June 20 and August 07, 2001	"Biorga N-liquid" (9.0 % N)	8 g N
May 06, 2002	"Biorga Quick" (10 % N, 1 % K_2O)	
June 14, 2002	"Biorga N-liquid" (9.0 % N)	12 g N
April 25, May 15 and June 23, 2003	"Biorga N-liquid" (9.0 % N	15 g N
April 12, 2004	"Horn flour" (14 % N)	12 g N
March 23, 2005	"Horn flour" (14 % N)	20 g N

by degradation, was compensated in February/March 2002, November 2002 and November 2004 by adding fresh sawdust. In November 2002 and 2004 all treatments were mulched by pine bark. In September before leaves turned red pH (H_2O) of the substrate was determined (2:1 water: substrate suspension with a glass electrode). Yield was evaluated by weighting fruits of each plant. Plant volume was measured after leave fall (formula : plant height * radius at medium plant height^2 * π).

Statistical analysis

Statistical analysis of data was done using JMP 4.0.2 (SAS incorp. Cary, NC, USA). Data were tested for normal distribution and homogeneity of variances. If necessary data were [$\log_{10}(x)$] transformed before conducting parametric analysis (ANOVA, linear or quadratic regression). Means were compared by the Tukey HSD test (α=0.05).

Results

Pot-Experiment 1: Substrate testing

The growth of young potted blueberries 'Bluecrop' over 5 seasons (1998–2002) expressed as the sum of fresh weight of one season-old tips was significantly influenced by substrate (data transformed: [$\log_{10}(x)$], two way ANOVA; Substrate: $F_{10,54}$=35.77; P<0.0001; Block: $F_{1,54}$=0.62, P=0.4353; Tukey HSD-Test (α=0.05)). The growth was highest in pots with peat reaching 503 ± 26.6 [a] g plant^{-1} (mean ± se [Tukey]); followed by the three sawdust-substrates: beech sawdust 285 ± 28.2 [b] g plant^{-1}, pine sawdust 278 ± 27.5 [b] g plant^{-1}, oak sawdust 266 ± 34.8 [b] g plant^{-1}. The mixed-substrates gave 264 ± 15.5 [b] g plant^{-1} (pine bark and pine sawdust), 223 ± 28.3 [bc] g (beech bark and beech sawdust) and 192 ± 10.9 [bc] g (oak bark and oak sawdust), respectively. A lower fresh weight was observed in the bark substrates with 167 ± 12.7 [c] g plant^{-1} in beech bark, 153 ± 14.2 [c] g plant^{-1} in pine bark, and 140 ± 6.4 [c] g plant^{-1} in oak bark. With only 59 ± 1.9 [d] g plant^{-1}, the growth in garden soil from Frick was lowest. Comparing the sawdust substrates to the peat substrate, plants in sawdust showed almost no growth in the first year and only little growth in the two following years (around 40 % of the peat substrate). In the fifth year growth rates of plants in sawdust substrates were comparable to growth rates in peat (Fig. 2). Growth rates of plants in garden soil from Frick were lowest in all years of experiment.

The cumulative volume shrinkage of the substrates over 4 years due to compacting and degradation was significantly different among the different substrates (Table 2). The most shrinkage was observed in the bark substrates.

Table 2. Shrinkage of substrates (two way ANOVA; Substrate: $F_{10,54}$=38.22, P<0.0001; Block: $F_{1,54}$=5.52, P=0.0225; Tukey HSD-Test (α=0.05) different letters show significant differences).

Substrate		Shrinkage (cm)
bark	oak	32 ± 1.7 [a]
	beech	29 ± 1.7 [ab]
	pine	29 ± 2.4 [ab]
bark mixed with sawdust	oak	23 ± 1.2 [bc]
	beech	27 ± 2.5 [ab]
	pine	19 ± 0.9 [cd]
sawdust	oak	19 ± 1.4 [cd]
	beech	23 ± 1.3 [bc]
	pine	14 ± 0.7 [de]
peat		9 ± 0.5 [ef]
garden soil		4 ± 0.5 [f]

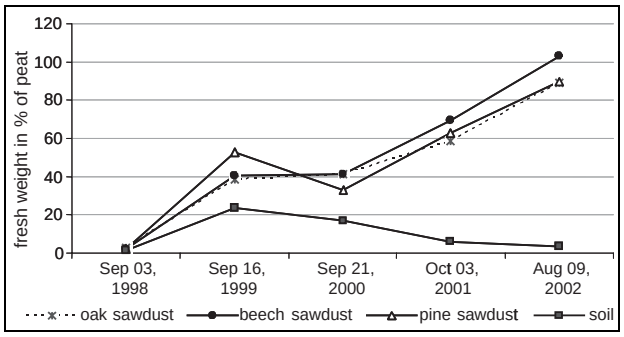


Fig. 2. Relative growth rate of potted 'Bluecrop' blueberries in different substrates from 1998 to 2002 (in % of the growth rate in the standard substrate peat).

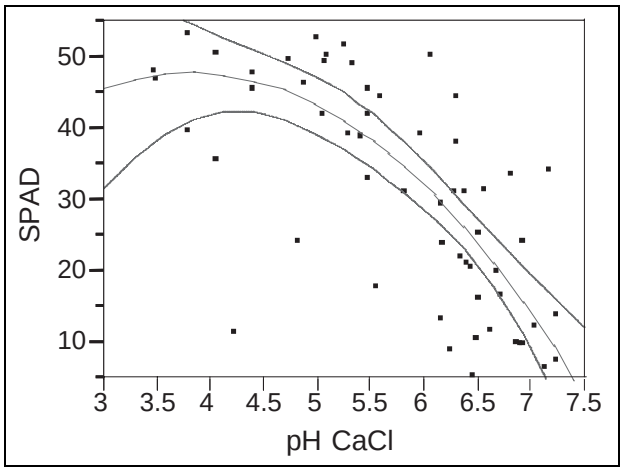


Fig. 3. Correlation between SPAD-value and pH measured in $CaCl_2$ [quadratic regression equation is SPAD = 109.95 – 12.95pH – 3.28(pH–5.78)^2, $F_{2,53}$=39.21, P<0.0001; r^2=0.60].

Larvae of *Trichius fasciatus* L. usually feed on detritus of deciduous trees like birch, beech or alder (ZAHRADNIK 1985). However, in this study we found larvae of *T. fasciatus* L. feeding on roots of *V. corymbosum* L.. In some cases the damages even led to death of plants. The incidence of larvae differed significantly between treatments. Highest numbers were found in oak sawdust with 38 ± 11.6 (mean ± se) larvae pot^{-1}, followed by beech bark mixed with beech sawdust (27 ± 8.1 larvae), beech sawdust (23 ± 9.4 larvae) and oak bark mixed with oak sawdust (16 ± 6.8 larvae). In all other treatments we found no (garden soil from Frick, peat, pine bark) or less than 2 larvae pot^{-1} (oak bark, pine sawdust, pine bark mixed with pine sawdust, beech bark).

During the whole testing period the pH (H_2O) of all substrates was never as low as at the beginning of the experiment: Oak sawdust pH 2.6, oak bark mixed with oak sawdust pH 3.3 and peat 3.1, respectively. Highest pH levels were observed in the garden soil of Frick with 6.6 and in beech bark with 5.6. All other substrates ranged between 4.1 and 5.3. Already six months after beginning of the experiment pH in oak sawdust increased from 2.6 to 6.5 (data not shown). Therefore, the pH of fresh substrates is not adequate to judge its suitability as a growing substrate. The average pH in the stabilized substrates (2000, 2001, 2002; two way ANOVA; Substrate: $F_{10,54}$=70.63; P<0.0001; Block: $F_{1,54}$=0.12, P=0.7291; Tukey HSD-Test (α=0.05) different letters show significant differences) was lowest in peat (4.7 ± 0.09 [f]) (mean ± se [Tukey]), followed by oak (5.3 ± 0.12 [e]) and pine sawdust (5.3 ± 0.10 [e]), pine bark (5.7 ± 0.08 [de]) and pine bark mixed with pine sawdust (5.7 ± 0.12 [de]), beech sawdust (5.8 ± 0.12 [d]), beech bark mixed with beech sawdust (5.9 ± 1.3 [cd]), oak bark mixed with oak sawdust (6.3 ± 0.05 [bc]), beech bark (6.7 ± 0.07 [b]), oak bark (6.8 ± 0.08 [b]) and garden soil from Frick (7.5 ± 0.03 [a]).

Pot-Experiment 2: Optimal pH in the pine sawdust

We assumed that optimal pH adjustment is where SPAD-values (chlorophyll-index) are highest. The measured SPAD values at the end of the growing season ranged between 5.8 and 53.8. PH levels measured in $CaCl_2$ ranged from 3.45 to 7.22. We found a correlation between the SPAD values and the pH measured in $CaCl_2$ (Fig. 3). Highest SPAD values were achieved at a pH level ($CaCl_2$) of 3.81. PH levels measured in water ranged from 3.94 to 7.94. For pH measured in water the quadratic term in the regression was not significant (quadratic regression: SPAD = 85.98 – 9.23pH + 1.20(pH – 6.02)^2, $F_{2,53}$=18.29; P<0.0001 r^2=0.40). There was a good correlation between pH ($CaCl_2$) and pH (H_2O) (linear regression: pH (H_2O) = 0.77 + 0.91pH ($CaCl_2$); $F_{1,54}$=263.37; P<0.0001 r^2=0.83). Consequently the optimal pH with the $CaCl_2$-method of 3.81 corresponds to a pH in H_2O of 4.23.

Field-Experiment 1: Irrigation water quality and bark mulching

The quality of the irrigation water and the bark mulching significantly influenced the pH (H_20) in the sawdust substrate (Fig. 4). Irrigation with hard and soft tap water led to a higher pH level than irrigation with rainwater and the control treatment without irrigation. The addition of S to hard water irrigated plots significantly lowered pH. Under the bark mulch cover the pH was significantly higher (5.1 ± 0.1 [a]) than without mulch cover (4.8 ± 0.13 [b]).

Irrigation water quality had no significant effect on the shrub volume (two way ANOVA; Water: $F_{4,9}$=1.19; P=0.38; bark mulching: $F_{1,9}$=26.88; P=0.0006; water*bark: $F_{4,9}$=2.05; P=0.17; Block: $F_{1,9}$=0.06, P=0.81; Tukey HSD-Test (α=0.05) different letters show significant differences). Bark mulching significantly increased the shrub volume (1256 ± 75 [a] dm^3) by 58.6 % compared to the plots without mulch (792 ± 65 [a] dm^3). We found a significant correlation between shrub volume and yield (linear regression: yield = 2000.30 + 2.52*Volume; $F_{1,18}$=18.13; P=0.0005 r^2=0.50). Yield was not significantly influenced by irrigation water quality (Fig. 5). In hard water irrigated plots with S treatment the yield tended to be highest, followed by treatment rain water. Bark mulching significantly increased the yield (5088 ± 274 [a]) by 24.7 % compared to the plots without mulch (4080 ± 380 [b]).

Field-Experiment 2: Cultivation system and pH-regulation

The cropping systems as well as the pH regulation significantly influenced the cumulative yield from 2000 to

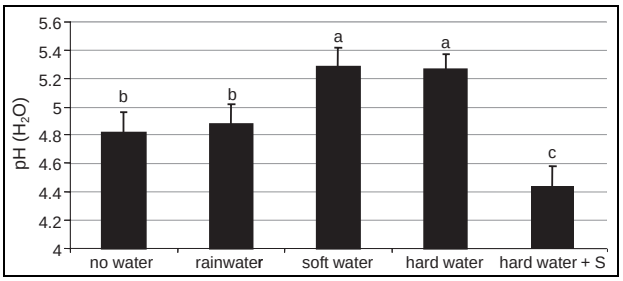


Fig. 4. Influence of irrigation water quality on pH level of substrate [two way ANOVA; Water: $F_{4,9}$=22.81, P<0.0001; bark mulching: $F_{1,9}$=14.81, P=0.004; water*bark: $F_{4,9}$=2.66, P=0.10; Block: $F_{1,9}$=13.94, P=0.005; Tukey HSD-Test (α=0.05) different letters show significant differences].

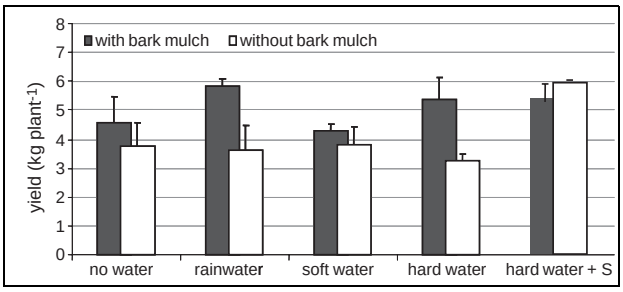


Fig. 5. Influence of irrigation water quality and bark mulch on yield per plant [two way ANOVA; Water: $F_{4,9}$=2.96, P=0.08; bark mulching: $F_{1,9}$=8.37, P=0.02; water*bark: $F_{4,9}$=2.21, P=0.15; Block: $F_{1,9}$=2.91, P=0.12; Tukey HSD-Test (α=0.05)].

2005 (data transformed [$\log_{10}$(x)]; 4-way ANOVA; cropping system: $F_{2,88}$=4.56, P=0.01; pH regulation: $F_{2,88}$=33.55, P<0.0001; cultivar: $F_{1,88}$=3.21, P=0.08; block: $F_{2,88}$=3.40, P=0.04; system * pH: $F_{4,88}$=1.54, P=0.20; cultivar * pH: $F_{2,88}$=2.44, P=0.09; system * cultivar: $F_{2,88}$=0.50, P=0.61; system * cultivar * pH: $F_{4,88}$=0.56, P=0.69). The yield per plant over six years of experimental period in the system deep ditch was significantly higher than in the system raised bed, whereas the yield in the system flat ditch was very close to the yield in the system deep ditch (Fig. 6). Influence of different pH regulation strategies were more pronounced: the yield in the S treated plots was more than two kilograms per plant higher than in the plots acidified with citric acid or in the plots without pH adjustment. Compared to the control without pH regulation citric acid increased the yield by 9.3 % and S by 55.4 % (Fig. 7). Yield was not influenced by cultivar of blueberries: on average 'Bluecrop' yielded 5.9 ± 0.23 kg plant^{-1} and 'Reka' yielded 5.5 ± 0.29 kg plant^{-1}.

We observed considerable fluctuations in pH levels between the years (up to 1.8 pH units), whereby pH values of all treatments followed the same pattern. Over the whole experimentation period only S significantly lowered the pH level (4.2 ± 0.04 [a]) (mean ± se [Tukey]; two-way ANOVA: cropping system: $F_{2,99}$=1.28, P=0.28; pH regulation: $F_{2,99}$=400.09, P<0.0001; system*pH: $F_{4,99}$=3.36, P=0.01) compared to the control without pH regulation (5.5 ± 0.04 [b]). Citric acid did not have a significant effect (5.5 ± 0.03 [b]).

The shrub volume was only influenced by the pH regulation method (data transformed [$\log_{10}$(x)]; 4-way ANOVA; cropping system: $F_{2,88}$=1.38, P=0.26; pH regulation: $F_{2,88}$=15.26, P<0.0001; cultivar: $F_{1,88}$=1.58, P=0.21; block: $F_{2,88}$=1.10, P=0.34; system * pH: $F_{4,88}$=2.06, P=0.09; cultivar * pH: $F_{2,88}$=0.86, P=0.43; system * cultivar: $F_{2,88}$=0.39, P=0.68; system * cultivar * pH: $F_{4,88}$=0.89; P=0.48): with 1341 ± 67 [a] dm^3 the volume was highest in the S treated plots (citric acid: 1013 ± 77 [b] dm^3, without pH regulation: 904 ± 36 [b] dm^3).

The cumulative volume shrinkage of the pine sawdust due to compacting and degradation was different among the cropping systems, but not among the acidification methods. Shrinkage was compensated by adding new substrate each year. Cumulated over 6 years the requirements for additional sawdust were highest in the flat ditch system were highest (263 ± 7.4 [a] L plant^{-1}; mean ± se [Tukey]), followed by raised bed (227 ± 8.3 [b] L plant^{-1}) and deep ditch (130 ± 5.7 [c] L plant^{-1}) (data transformed [$\log_{10}$(x)]; 2-way ANOVA; cropping system: $F_{2,99}$=104.67, P<0.0001; pH regulation: $F_{2,99}$=2.22, P=0.11; system*pH: $F_{4,99}$=1.70, P=0.16).

Discussion

At the beginning of our experiments an organic upper-land blueberry production was considered to be unrealistic because of too many unsolved problems like no alternative to peat, no method for substrate acidification, no suitable cultivation system, no possibility for adequate N-fertilization. Therefore, we started to conduct several studies to optimize each of the critical factors in a first phase. Then we combined best methods into a close to commercial production experiment. With this strategy we finally succeeded in developing complete cultivation recommendations for the commercial organic blueberry production.

In the first experiment we tested different substrates in order to find an alternative to peat. The growth of young *V. corymbosum* L. plants was best in peat and worst in alkaline garden soil. Substrates of pure sawdust were the best alternatives to peat, followed by mixtures of sawdust and bark. Low growth rates were found in pure bark substrates. In addition to the poor growth results, bark substrates showed a high shrinkage due to compacting and degradation. Therefore sawdust seems to be the better substrate choice for commercial organic blueberry production. Growing rates of young plants in sawdust were low during the first three years, and reached the level of peat in the fifth year. This might be due to the advanced decomposition oft the sawdust. To achieve a sufficient growth (adequate to peat) in the first two years it is recommended to apply quickly available organic N-fertilizer during this period. In the first experiment we also compared sawdust from different trees (beech, pine or oak). With an average pH near 5 in the third, fourth and fifth year of the trial oak and pine sawdust were the most suitable substrates, concerning the criterion of pH-value. During our trials we found larvae of *T. fasciatus* L. feeding on roots of *V. corymbosum* L.. In some cases the damages even led to death of plants. These larvae were particularly attracted to beech and oak sawdust, whereas beetles avoided pine sawdust substrates. In addition, the low

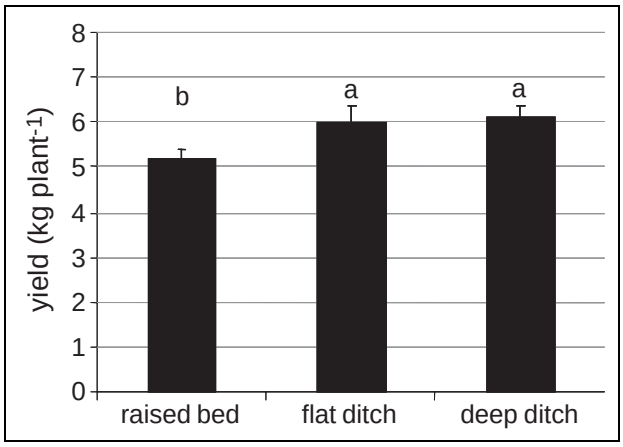


Fig. 6. Influence of cultivation system on cumulative yield of 'Bluecrop' and 'Reka' blueberries (kg plant^{-1} over 6 harvest years), grown in pine sawdust substrate. Statistical analysis: 4-way ANOVA, details see text; Tukey HSD-Test (α=0.05) different letters show significant differences.

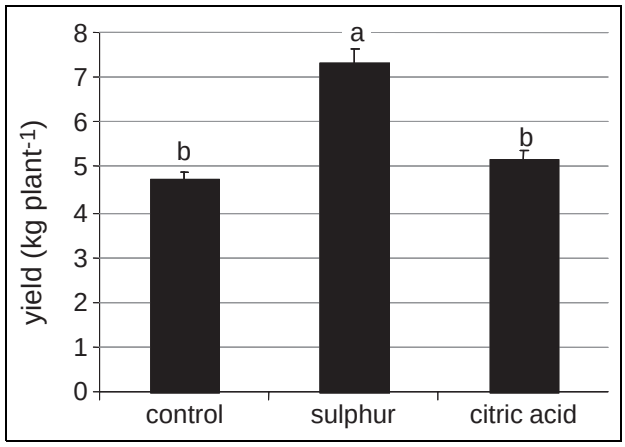


Fig. 7. Influence of the pH regulation method on yield of 'Bluecrop' and 'Reka' blueberries (kg plant^{-1} over 6 harvest years, average of all cultivation systems), grown in pine sawdust substrate. Statistical analysis: 4-way ANOVA, details see text; Tukey HSD-Test (α=0.05) different letters show significant differences.

shrinkage rate of pine sawdust, made this substrate preferable to hardwood sawdust. Until now only few publications are available on alternative growing substrates: Black and Zimmermann (2002) tested industrial and municipal by-products like coal ash, composted sewage sludge and leaf compost as substrates for *V. corymbosum* L. production. They determined, that coal ash - compost mixtures show potential to improve unsuitable upland soil if the pH of the substrate is adjusted to 4.5 by S. Gagnon et al. (2003) indicate in their study that paper mill sludge, when used at low rates, improves lowbush blueberry (*V. angustifolium* Ait.) yield and the soil enzyme activity on low fertility sand. However, the availability of these substrates is complicated or expensive in Central Europe. Therefore we assume that pine sawdust is the best alternative substrate to peat for blueberry production in Switzerland/Central Europe. All further trials were conducted using pine sawdust substrates.

A second experiment was conducted to determine the optimal pH level in the pine sawdust substrate. As an indicator for plant vitality we assessed the content of chlorophyll in leaves (SPAD-method). A pH level of 3.81 measured in $CaCl_2$ and 4.23 when measured in H_2O was found to be the most suitable. Because of this substantial difference between the two methods of pH determination it is recommended to mention the method when pH values are indicated. We assume that the $CaCl_2$-method is more suitable to measure the plant relevant pH of the growing substrate. Many studies are available on pH requirements of blueberries: Coville (1910) stated that *V. corymbosum* L. production is not possible in soils of neutral or alkaline reaction. Harmer (1944) narrowed the optimum soil pH (extraction medium ubknown) for *V. corymbosum* L. production between 4.0 and 5.2. Other studies report a growth decline at soil pH below 3.8 (Merill 1944, unknown extraction media) and above 5.2 (Bailey 1941, unknown extraction media). Similarly, and confirming our results Haynes and Swift (1985) found that plant dry matter of *V. corymbosum* L. planted in peat increased consistently when pH (H_2O) was lowered from 7.0 to 4.6 but, declined when pH was lowered further to 3.8. Heckmann et al. (2002) suggest a pH level of 4.8 (unknown extraction media) as a target value for *V. corymbosum* L. production. Holmes (1960) and Brown and Draper (1980) suggested that the main reason for insufficient plant growth under high soil pH condition is insufficient iron uptake. Haynes and Swift (1986) suggested that a deficiency of Mn rather than Fe appeared to limit growth at high soil pH. Cain (1952) noted that soil pH is not necessarily a direct factor of controlling iron absorption because blueberries growing on soils of relatively high pH often contain as much iron in their leaf tissues as blueberries showing no symptoms of deficiency. Thus, he assumed a deficiency of plant available ammonium N to be the limiting factor.

According to Peterson et al. (1988) *V. corymbosum* L. performed twice as good with ammonium N nutrition compared to nitrate N. In line to this, Dancer et al. (1973) reported that at pH levels below 5 (extraction medium unknown), ammonium N remains longer in soil due to a reduced nitrification rate. In an organic production system the N supply depends entirely on the nitrification of the organically bound N sources, and explains the importance of low pH values in an organic production system. We assume a pH level of 3.5 to 4 ($CaCl_2$) or 4 to 4.5 (H_2O) to be most suitable for a production system using pine sawdust.

The aim of the first field experiment was to evaluate the influence of irrigation water quality on substrate pH level. According Spiers and Braswell (1992) irrigation water quality (low EC, low, Na^+, Ca^{2+} and other cations) is important in blueberry (*V. ashei* Reade) production. In our experiment water quality (hardiness) significantly influenced substrate pH but had no influence on volume of plants or yield. The average pH (H_2O) in the control treatment (without irrigation) and in the rainwater irrigated plots was 4.8 and 4.9, respectively. Plots irrigated with the tap-water with a hardiness of 357 and 89 mg L^{-1} $CaCO_3$ showed a pH of 5.3. Spiers and Braswell (1992) also experienced that the addition of S at rates of up to 1.120 kg ha^{-1}on a fine sandy loam soil with a pH of 6.1 to

6.4 were not sufficient to overcome the negative effects of Na and Ca deriving from irrigation water. In our study, the addition of 28 g S plant^{-1} and year (93 kg ha^{-1}with 3.333 plants ha^{-1}) to hard water irrigated plots in sawdust significantly lowered pH to 4.4. Our results indicate that hard water irrigation with additional acidification is most suitable to achieve the optimal pH level of near 4 as mentioned above. The effect of unsuitable hard irrigation water can easily be compensated by adding small amounts (about 30 g year^{-1} plant^{-1}) of S to the pine sawdust substrate. Therefore, expensive and complicated equipment like rain water tanks or water demineralisation are not necessary.

The first field experiment also showed that mulching the sawdust ridges with pine bark can significantly increase growth rates of plants by 59 % and yield by 25 %. Different authors also showed an increased yield of *V. corymbosum* L. after mulching with bark or sawdust (Haynes and Swift 1986) or after organic matter was mulched or incorporated in mineral soils (Moore 1993). Spiers (1998) noted that mulching with pine bark improved plant growth and fruiting of southern highbush blueberry more than irrigation or soil incorporated peat moss. Pine bark mulching can also increase growth of *V. ashei* Reade (Krewer et al. 2002). According to Starast et al. (2002) growth of half-highbush (*V. corymbosum* L. x *V. angustifolium* Ait.) was best when cultivated in peat, sawdust mulch applied on mineral soil did not increase growth. According Sanderson and Cutcliffe (1991) a 5 cm layer of sawdust mulch applied after planting (*V. angustifolium* Ait.) increased the yield. However, sawdust mulch applied as a layer of 10 cm did not increase yield, in contrary plant survival was reduced. There are different explanations on the mode of action of mulching: Gustavsson (1999) reported that mulch of peat moss and pine needle litter on a sandy mineral soil lowered the pH from 5.6 to 4.6 and 4.7, respectively, in cultivated lingonberry (*Vaccinium vitis-idea* L.). In our experiments pH level of pine sawdust substrate was significantly increased from 4.8 to 5.1 by bark mulch covering. A better water balance is another explanation for the positive effects of mulch: Seedlings of *V. angustifolium* Ait. showed a higher water stress tolerance when growing under mulches (Hicklenton et al. 2000) and Pliszka et al. (1997) noted that mulching highbush blueberry crops with pine bark increased water retention of soil profile and decreased soil temperature in the rooting zone. Patten et al. (1988) showed that sawdust mulch applied on a fine sandy loam soil increase the growth of drip-irrigated plants (*V. ashei* Reade), but had no influence on low-volume spray emitter-irrigated plants. From our observations we suppose that growth and yield improvements found in bark-mulched plots are mainly due to a more balanced moisture availability inside the sawdust substrates. Moreover the quicker decomposition of sawdust under the bark-mulch layer might increase the availability of nutrients.

In the second field experiment under conditions close to commercial production we showed that cultivation system and the acidification method significantly influenced yield over 6 years. The yields in the cultivation systems deep ditch and flat ditch were one kilogram per plant higher yield than in the raised bed system. We assume this is due to less evaporation and therefore a better moisture availability for the plants in the systems deep ditch and flat ditch. No differences were found between *V. corymbosum* L. 'Reka' and 'Bluecrop'. Schwärzel and Schubert (2003) also found a decrease of 10–40 % in yield per plant when cultivated on substrate ridges compared to natural suitable soils, however, as a result of smaller shrub size, the specific yield (kg m^{-3} shrub volume) increased. Therefore, an improvement in picking and cultivation performance can be expected. In our experiments plant growth and pH level in the substrate were affected by acidification method but not by cultivation system. Effects of acidification method on the yield were more pronounced than effects of cultivation system: S treated plots gave a 55 % higher yield than control plots without acidification and 42 % higher yield than plots treated with citric acid. Although citric acid was added in same acidity equivalents as S, it had nearly no effect on the pH compared to the control. The average pH level (H_2O) over 6 years in the S treated plots was 4.3, in citric acid treatment and untreated plots 5.5. This might be due to higher volatilization or leaching rates of citric acid. This shows that plant growth and yield are highly dependent on the effectiveness of the acidification method. Cummings et al. (1981) noted that the addition of sawdust is more helpful for blueberry growth (*V. ashei* Reade) than lowering soil pH with S. However, Peterson et al. (1987) suggested that the combination of sawdust and acidification with S is most effective. We observed considerable fluctuations in pH levels between the years (up to 1.8 pH units), which have no obvious explanation such as higher precipitation. However, pH-values of all treatments followed a quite parallel pattern.

The need of sawdust to establish and to maintain the three cropping systems was different between treatments. For the systems flat ditch and raised bed nearly double amount of sawdust is needed compared to the system deep ditch. Depending on costs of sawdust this fact may be relevant. However, for the system deep ditch additional material like water permeable film, impermeable film and grit is needed. For the installation of one 100 m long row in our experiment, these costs and costs for machine employment summed up to 1350 € for the system deep ditch, 600 € for the system flat ditch and 450 € for the system raised bed. The labour input required to install a 100 m long row was 33 h for the system deep ditch, 12 h for the system flat ditch and 6 h for the system raised bed. For commercial organic blueberry production we recommend to use the flat ditch cultivation system because of its good plant performance and reasonable requirements for material. However, the raised bed cultivation system might be an alternative "low-input"-system.

In conclusion, we could show that organic blueberry production on alkaline soils is feasible without peat and/or plastic film. Pine sawdust was shown to be the most suitable alternative to peat. The cultivation system flat ditch is recommended based on economic considerations. Bark mulching on the sawdust substrate increases plant growth and yield. Rain water or tap water can be used for irrigation. If hard water is used, a substrate acidification with S is necessary. Independently from the cultivation system an optimal soil pH is of central importance for plant performance. To adjust a pH level, an adequate acidification of the substrate is compulsory. In our study S was much more effective than citric acid. Depending on soil pH the substrate pH should be adjusted by addition about 30 g S per running meter and year to reach the optimal substrate pH of 3.5–4 ($CaCl_2$) or 4–4.5

(H_2O).The $CaCl_2$-method gave more meaningful results of plant-relevant pH level in the substrate. We achieved good results with a fertilisation of 60 kg N ha^{-1} (18 g $plant^{-1}$) in the first spring after plantation, and with 30–60 kg ha^{-1} (9–18 g $plant^{-1}$) in the following years.

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