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The influence of forced air movements on greenhouse climate and plant growth

Mekanisk luftfordelings indflydelse på væksthusklima og plantevækst

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Summary

Begonia x hiemalis, Ficus benjamina, Fuchsia x hybrida, and *Rose hybrida* were grown under forced and natural air movements during autumn and winter. The air humidity, canopy temperature, and CO_2 consumption was lower in the greenhouse with forced air movements compared to a greenhouse with natural air movements. A remarkable drop in canopy temperature was observed under forced air movements when the screens opened in the morning.

Under forced air movements an increase in plant height and dry matter content was found in *Ficus benjamina* in one of two experiments. In *Fuchsia x hybrida* the fresh weight and time to flowering increased under forced air movements. *Rosa hybrida* responded only to forced air movements in one experiment, where number of flower buds and time to flowering were increased. Opposite effects on plant growth and development were found in the two experiments with *Begonia x hiemalis* in regard to plant width, plant height, and plant quality.

Key words: Air humidity, air movements, air temperature, *Begonia x hiemalis,* canopy temperature, CO_2 consumption, fans, *Ficus benjamina, Fuchsia x hybrida, Rosa hybrida.*

Resumé

Ficus benjamina, Fuchsia x hybrida, Begonia x hiemalis og *Rosa hybrida* blev dyrket med og uden mekanisk luftfordeling.

Luftfugtigheden var lavere i væksthuset med mekanisk luftfordeling og desuden blev doseringstiden med CO_2 kortere pga. den forøgede luftcirkulation. Åbning af isoleringsgardinerne om morgenen medførte et markant fald i bladtemperaturen i væksthuset med mekanisk luftfordeling. Mekanisk luftfordeling øgede plantehøjden og tørstofprocenten hos *Ficus benjamina,* men kun i det ene af to forsøg. Produktionstiden og friskvægten blev forøget hos *Fuchsia x hybrida.* Hos *Rosa hybrida* blev antallet af blomster forøget og produktionstiden forlænget, men mekanisk luftfordeling havde kun virkning i det ene af to forsøg. *Begonia x hiemalis* reagerede modsat i de to forsøg mht. højde, bredde og kvalitet af planterne.

Nøgleord: *Begonia x hiemalis,* bladtemperatur, CO_2-forbrug, *Ficus benjamina, Fuchsia x hybrida,* mekanisk luftfordeling, luftfordelere, luftfugtighed, lufttemperatur, *Rosa hybrida.*

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Introduction

This paper deals with the influence of forced versus natural air movements on air humidity, canopy temperature, and plant growth, and development.

Increasing the air speed in the greenhouse should result in a better heat distribution, but will expose a greater air volume to the cold glass surface. The water vapor condensation on the glass results in a lower air humidity which could lead to a reduction in fungal diseases. Exchanges of heat, water vapor, and CO_2 between the leaf and the surrounding air takes place by diffusion through the boundary layer. High air speed will reduce the thickness of the boundary layer, which will have influence to a greater or lesser extent on convective heat exchange, transpiration, and CO_2 supply.

The use of mobile benches has reduced the air movements considerably because the benches are close together. The reduction in natural air movements has resulted in uneven heat distribution, fungal diseases, heterogeneity in plant development, and flowering.

In the trial forced air movements were created by use of propeller fans spaced within an experimental greenhouse, and the effects determined by comparing with a reference greenhouse without fans. Two experiments were conducted, experiment 1 in the autumn and experiment 2 in the winter. Thus, the effects of continuous running of the fans is emphasized in this study.

Materials and methods

The experiment was performed in two separated east-west orientated greenhouses with a ground surface of 8 m × 16 m. The cladding material was single glass and the greenhouses had continuous ridge ventilation. The greenhouses were equipped with top going shading screens (LS15, Ludvig Svensson, Kinna, Sweden). In the greenhouse with forced air movements, two fans (Nordic 2S 90, Vortice, Italy) were installed. They were placed 4 m from the gables leaving 8 m distance between them. They were positioned 2 m above the plant canopy and the air jet was directed downward. Each fan had three wings and a diameter of 0.9 m. The air movement was estimated at 1280 m^3/h per fan at 270 rpm. The air speed was 2 m/s measured with a hot wire anemometer (Thermo-anemometer GGA 235, Wallac, Turku, Finland) 2 m vertically beneath the fan. The air speed resulted in heavy fluttering leaves. The air speed measured at the top of the canopy between the fans was 0.6-0.7 m/s, and no fluttering of the leaves was observed. In the greenhouse without fans the air speed was 0.2-0.4 m/s. The air speed over the canopy in both greenhouses was estimated by the means of cold smoke.

The plant canopy temperature was measured in the middle of each greenhouse with an infra-red thermometer (Heimann KT15, Heimann GmbH, Wiesbaden, West Germany) with detector A and lens type M. It was held 0.6 m above the plant canopy and pointed downwards at an angle of about 45° from horizontal. The area measured was 0.1 m^2. The canopy temperature was measured on *Ficus pumila* L.

The photoperiod was prolonged on 18 h with artificial light, which was turned on 6 h after sunset and turned off at sunrise. The light source was 400 W high pressure sodium lamp (SON-T, Philips, Eindhoven, The Netherlands).

CO_2 enrichment to 900 µl/l was used during the whole photoperiod when the ventilators were closed. In each greenhouse two outlets for CO_2 supply were used and one inlet for measuring the CO_2 concentration. The outlets were placed 0.8 m over the plant canopy and was placed ⅓ of the greenhouse length from each gable. The inlet for measuring the CO_2 concentration was placed in an aspirated screen located 0.25 m above the canopy. The CO_2 flow was 0.6-0.8 l/min and the operation time for the valves controlling the CO_2 supply was automatically recorded.

Air temperature and humidity were measured in the same aspirated screen where the CO_2 inlet was placed. The set point for heating was 18°C and ventilation at 26°C. Set point for the root zone heating was 19°C. The root zone temperature was measured with a Pt100 sensor in the middle of a pot in the same area where the canopy temperature was measured. Shading screens were closed whenever the outdoors irradiance exceeded 500 W/m^2 (300-2500 nm). During night the shading screens were used as thermal screens.

Four species of pot plants, *Begonia x hiemalis* Fotsch., cv. Schwabenland, *Ficus benjamina* L., *Fuchsia x hybrida* Voss, cv. Kiss and *Rosa hybrida* L., cv. Red minimo were used in the experiment.

In both experiments with *Begonia x hiemalis* 9 week old plants with one plant per pot were used.

In the two first weeks of the experiment the plants were short day treated. Three weeks after start of the experiment the plants were thinned to 20 plants/m^2. The photon flux density was 39 ± 5 μmol/m^2·s measured in the top of plant canopy. The first experiment was conducted from 20 October 1988 to 10 January 1989, and the second from 13 January 1989 to 28 March 1989.

In both experiments with *Ficus benjamina* 6 week old plants with two plants per pot were used. The plants were spaced with 40 plants/m^2 and the photon flux density was 35 ± 5 μmol/m^2·s measured in the top of plant canopy. The first experiment was conducted from 19 October 1988 to 4 January 1989, and the second from 18 January 1989 to 29 March 1989.

Fuchsia x hybrida was only used in one experiment conducted from 5 January 1989 to 17 March 1989.

In the experiment 6 week old plants with one plant per pot was used. At start of the experiment the plants were pinched to three nodes, and were short day treated (11 h) for 12 days. One week after short day treatment the plants were spaced with 30 plants/m^2. The photon flux density was 32 ± 3 μmol/m^2·s measured in the top of plant canopy.

In both experiments with *Rosa hybrida* L. 4 week old plant were used and in each pot were 4 cuttings. The plants were pinched to 3 nodes just before the start of the experiment and were spaced with 38 plants/m^2. The photon flux density was 41 ± 4 μmol/m^2·s measured in the top of the canopy. The first experiment was conducted from 20 October 1988 to 8 December 1988, and the second from 12 January 1989 to 28 February 1989.

All the plant species were grown in flooding benches and were automatically irrigated with water containing fertilizer. The plants were irrigated when 2 mm of evaporation had occurred. *Rosa hybrida* was fertilized with 0.87 g/l 11.4 N – 1.4 P – 10.3 K. *Begonia x hiemalis, Ficus benjamina* and *Fuchsia x hybrida* were fertilized with 0.75 g/l 10.2 N – 1.8 P – 8.1 K.

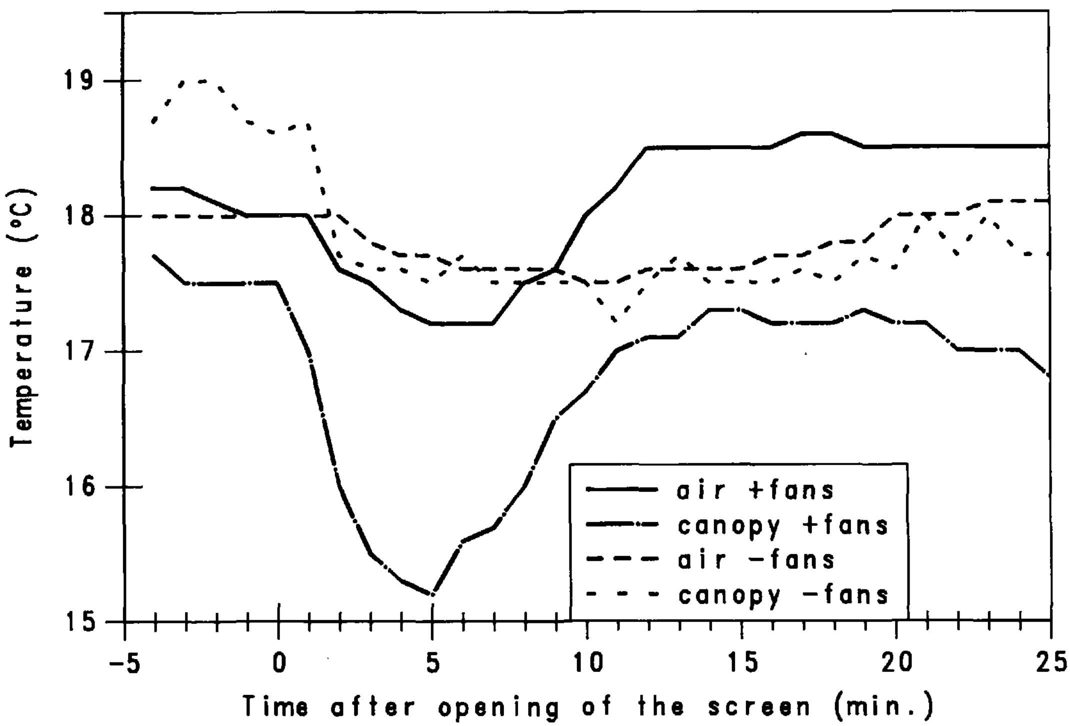

Fig. 1. The effect of forced air movements on air and canopy temperature when the screens opened in the morning. The opening of the screens started at 0, and the outside temperature was 2.8°C. The artificial light was still on when the opening of the screens occurred.

In each experiment 10 plants per plot and 4 replications were used. The statistical significance was determined by analysis of variance.

Results

The mean canopy temperature was 1.5°C lower in the greenhouse with fans compared to the greenhouse without fans. In the greenhouse without fans the canopy temperature was close to the air temperature and deviated ± 0.2°C, when the measurements were made between 9 a.m. and 3 p.m. The measurements made under natural air movements are in agreement with *Amsen* and *Nielsen* (1).

The mean canopy temperature was 0.2°C higher than the air temperature when the artificial light was running and screens were closed in the greenhouse without fans. Under the same conditions the mean canopy temperature was 1.2°C lower than the air temperature in the greenhouse with fans.

A remarkable drop in canopy temperature was observed when the screens opened, and especially when the temperature outdoors was low (Fig. 1).

The mean air humidity was lower in the greenhouse with fans compared to the greenhouse without fans, but had the same profile. In the experiment the air humidity was expressed by delta-T, which indicate the difference between air temperature and dew point temperature. The typical difference between the two greenhouses was a delta-T value of 1°C, and the humidity was lowest during night, and highest in the middle of the day (Fig. 2).

The relative operation time for CO_2 dosage was reduced by 20% when forced air movements were used.

Ficus benjamina – Only in experiment 2 an effect of forced air movements was found. Total plant height, accession in plant height and dry matter content increased (Table 1).

Fuchsia x hybrida – Forced air movements decreased time to flowering and increased fresh

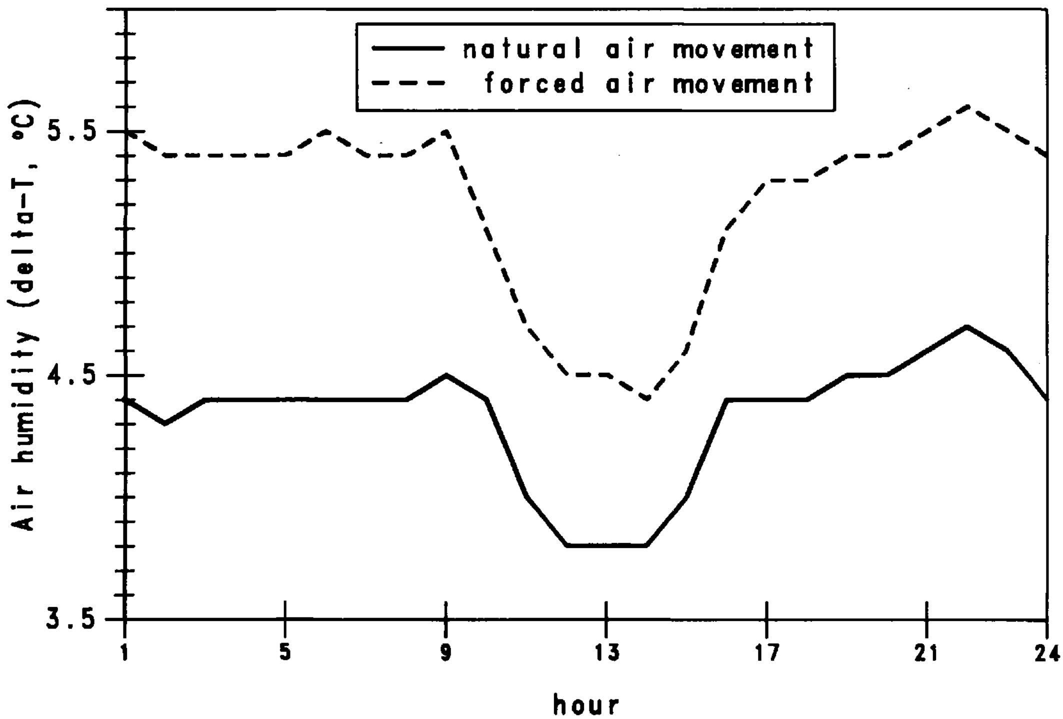

Fig. 2. Diurnal variation in air humidity under forced and natural air movements expressed as delta-T.

Table 1. *Ficus benjamina.* Effect of air distribution on total plant height, accession in height, and dry matter content[1].

	Height (cm)		Acession in height (cm)		Dry matter content (%)	
	Exp. 1	Exp. 2	Exp. 1	Exp. 2	Exp. 1	Exp. 2
Natural air movement	29.1	32.2b	12.2	13.5b	18.5	21.7b
Forced air movement	28.2	34.8b	12.0	15.5a	18.9	22.4a

[1] In all tables, value in each column accompanied by different letters differ significantly at P = 0.01.

weight. Plant height, number of inflorescence, and laterals, and dry weight was unaffected (Table 2).

Begonia x hiemalis – The plant response to forced air movements was different in the two experiments (Table 3). In experiment 1 the plant width was unaffected, but was increased in experiment 2 in the treatment with forced air movements. The plant height, and quality was affected by the treatments but opposite effects were found in the two experiments. In experiment 2 forced air movements increased the plant height as it did with *Ficus benjamina.* The best quality was obtained under natural air movements in experiment 1. The opposite effect was obtained in experiment 2 where the best quality was obtained under forced air movements. Time to flowering was only affected in experiment 1 where the shortest time to flowering was found under natural air movements.

Rosa hybrida – In experiment 1 the number of flower buds per pot and time to flowering increased in the treatment with forced air movements (Table 4).

Discussion

In many experiments with air speed measurements on a single leaf have been used. When leaves are close together their boundary layers are likely to join and when this happens they cannot be considered as individual elements. It can therefore be very difficult to apply information and results from a single leaf reaction to the whole canopy. Also differences between short and long term experiments are pronounced, because changes in the water balance of the plant and anatomical changes influence the results.

Transpiration is able to cool the leaf several degrees below the leaf temperature which would occur in the absence of transpiration in still air (6). *Gates* (6) concluded that further energy exchange at negative difference between leaf and air temperature, only could happen by reradiation and free convection. Forced convection increases or decreases leaf temperature depending on air temperature and air speed (6,13). In another experiment (4) it was found for air speed of 0.9, 2.25, and 4.50 m/s, that the leaves were warmer than air temperature up to an air temperature of

Table 2. *Fuchsia x hybrida.* Effect of air distribution on plant height, number of laterals, and inflorescences, fresh- and dry weight, and time to flowering.

	Height (cm)	Number of laterals	Number of inflorescences	Fresh weight (g)	Dry weight (g)	Time to flowering (days)
Natural air movement	27.7	5.3	10.0	94.8b	9.3	70.3b
Forced air movement	28.6	6.0	9.3	110.8a	10.5	67.9a

Table 3. *Begonia x hiemalis.* Effect of air distribution on plant width, plant height, quality[2)], and time to flowering.

	Plant width (cm)		Height (cm)		Quality		Time to flowering (days)	
	Exp. 1	Exp. 2	Exp. 1	Exp. 2	Exp. 1	Exp. 2	Exp. 1	Exp. 2
Natural air movement	30.2	20.8b	21.0a	22.6b	8.3a	7.6b	73.4b	71.2
Forced air movement	28.7	24.0a	19.7b	23.8a	7.7b	8.4a	80.8a	70.9

[2)] Quality grade 0-9, 9 best.

35°C. If the air temperature was higher than 35°C, the leaf temperature was lower than the air temperature at the same air speeds.

The experiment was conducted in a wind tunnel, and irradiance was 872 W/m^2, and the plant species was *Xanthium strumarium* L. In the same experiment (4) it was found that an increase in air speed caused an increase in convective heat loss and a decrease in transpiration. When leaf temperature was above air temperature, stomatal apertures were wider at a leaf temperature of 30°C than 14.6°C. In present experiments the drop in canopy temperature when the screens were opened in the morning is a result of convective cooling. The cold air over the closed screens is drawn down and the canopy is exposed to the cold air.

Phaseolus vulgaris L. was grown at a range of air speeds (0-1.6 m/s), and almost no effect of wind on transpiration were found (8). The plants were exposed to the air speeds over a period of 3 weeks, and it was concluded that an adaption to the wind conditions had occurred. In an experiment with intermittent exposure to air speed the response of transpiration rate in *Cryptomeria japonica* showed an increase in the rate, when air speed was increased. The increase in transpiration rate was followed by a gradual decline until the rate was below that recorded for calm conditions (10). The reduced transpiration rate could be due to a stomatal closure because of an induced water deficit. In the present experiment a difference of 1.4°C was found between forced and natural air movements under artificial light and the shading screens closed. The difference can only be explained by a higher transpiration rate under forced air movements, because the radiation levels are the same and there is no exposure to the cold glass surface.

Yabuki and *Miyagawa* (12) measured change in diffusive resistance in cucumber leaf depending on air speed and RH. An increase resulted in a rapid decrease in the diffusive resistance and further increase over an air speed of 0.5 m/s increased the diffusive resistance.

In the same experiment (12) the increment in dry weight followed the changes in diffusive resistance. Increase in dry matter content could be

Table 4. *Rosa hybrida.* Effect of air distribution on inflorescences per pot, number of flower buds per pot, and time to flowering.

	Number of inflorescences		Number of flower buds		Time to flowering (days)	
	Exp. 1	Exp. 2	Exp. 1	Exp. 2	Exp. 1	Exp. 2
Natural air movement	12.6	9.1	27.6b	25.2	41.0b	45.8
Forced air movement	13.2	8.8	30.1a	24.5	43.9a	46.8

due to a higher water uptake due to a higher transpiration, leading to an elevated uptake of nutrition. Only in *Ficus benjamina* a higher dry matter content was obtained, and only in experiment 2.

Rawson et al. (9) found that the rate of photosynthesis and diffusion resistance in attached leaves was unaffected of air humidity.

A decline in the rate of photosynthesis with increasing air speed has been reported by *Bozarth et al.* (3). The decline in photosynthesis was especially pronounced at low humidities (50-60 RH). The rate of photosynthesis was highest with an air speed of 1.25 m/s and 80 RH after which it declined.

For *Rosa hybrida* L. cv. Samantha an increase in the photosynthetic rate in mature leaves was found when temperature increased from 15 to 25°C (3).

Under constant light conditions, a lowering of temperature from 20°C to 10°C or lower over a period of 2 min, caused a burst of CO_2 from wheat leaves. The lowering of the temperature resulted in a decrease of photosynthesis, and after reaching a minimum, the CO_2-uptake increased and was maintained at a lower constant level (11).

Grace and *Russel* (7) found morphological changes in grasses grown at an air speed of 1 m/s compared to plants grown in calm conditions. Leaf length and width were reduced under windy conditions resulting in a smaller leaf area. *Kalma* and *Kuiper* (8) found a decrease in leaf area in *Phaseolus vulgaris* L. when plants were grown at an air speed over 1 m/s.

The biochemical processes in the plant depends on the tissue temperature. The leaves of *Ficus pumila* are thin so the surface temperature is assumed to be close to the tissue temperature. All things considered a lower tissue temperature results in a reduced growth rate, unless other factors are compensating.

Pot plants are grown in small pots with a little soil volume for water retention. As a consequence, plants may dry out rapidly due to a higher evapotranspiration caused by forced air movements. *Armitage et al.* (2) found for *Pelargonium x hortorum* that it took 3 days before net photosynthesis returned to maximum upon rewatering after the plants were subjected to water stress. After being subjected to water stress the net photosynthesis never attained the same level as before exposure to water stress.

Forced air movements increased water consumption due to higher evapotranspiration, so the plants grown under these conditions were irrigated more frequently.

The CO_2 profile in the plant canopy in *Glycine max* L. altered through the day. A lower CO_2-concentration in the upper fourth of the canopy than in the air above the plant canopy has been reported (5). In the upper fourth the smallest fluctuation was found. The highest CO_2-concentration and fluctuation was always measured in the lower forth of the canopy, and was consistently higher than the CO_2-concentration in the air above the canopy. The characteristics of the profile depended on the row spacing of the plants.

It is assumed that forced air movements insure no undersupply of CO_2 in the uppermost part of the canopy. The experiment shows indirectly that the CO_2 distribution is uneven and that CO_2 only slowly dispersed in the greenhouse air.

Conclusion

It is recommended that fans should not be used when the thermal screens open in the morning. It is beneficial to let the fans run, when pure CO_2 is supplied to the greenhouse air. The fans can be used for lowering the air humidity or increasing transpiration rate but the canopy temperature should be taking into account.

A control system for the fans should be developed taken air humidity, energy consumption, heat distribution, outdoors climate, canopy, and air temperature into account for increasing plant production.

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