# Air movement and boundary layers

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***Abstract*—Air movement influences crop performance by modifying the leaf boundary layer, the relatively still air adjacent to a leaf surface. This layer resists sensible-heat transfer and the diffusion of water vapour and carbon dioxide, so its thickness and disturbance affect leaf temperature, transpiration and gas exchange. This paper synthesises evidence on the physiological significance of this process in controlled crop environments. Direct airflow research shows that changing low-velocity airflow alters boundary-layer conductance, leaf temperature, transpiration, stomatal regulation, photosynthesis and growth. These effects are conditional: increased air movement can reduce resistance to exchange, but it can also elevate evaporative demand, promote stomatal closure and constrain growth. The paper distinguishes leaf boundary-layer exchange from related root-zone transport and considers interactions with radiation, humidity and temperature. It concludes that air movement is best understood as a modifier of leaf microclimate rather than an independently beneficial input. The principal evidence gap concerns how airflow distribution, vapour pressure deficit and crop architecture combine to determine responses across crops and growing conditions.**

## I. Introduction

The air at a leaf surface can differ materially from the bulk air of a growing environment. A leaf boundary layer forms when air immediately adjacent to the surface is relatively still, creating resistance to sensible-heat transfer and to diffusion of water vapour and carbon dioxide. This resistance makes air movement physiologically important because it affects the local conditions under which leaves exchange energy, water and carbon. Direct research on sustained low-airflow treatments has linked boundary-layer conditions with changes in conductance, leaf temperature, transpiration, gas exchange and growth [1]. Accordingly, a room-level temperature or humidity measurement alone cannot fully describe the conditions experienced by a leaf [2].

Air movement changes the boundary layer by disturbing and renewing air near the leaf surface. When that action reduces boundary-layer resistance, heat and water vapour can transfer more readily between leaf and air, while carbon dioxide exchange may also be altered. In lettuce, contrasting low-velocity airflow regimes changed leaf-surface microclimate, plant transpiration, stomatal regulation, photosynthesis and growth [1]. These linked responses show why airflow cannot be interpreted only as a cooling factor or only as a humidity factor. It modifies a pathway through which energy balance, plant water status and carbon assimilation interact [3].

Greater air movement is not automatically associated with improved plant performance. In the available direct study, enhanced airflow increased transpirational demand and was accompanied by dynamic stomatal closure. That response improved intrinsic water-use efficiency but did not fully offset water loss, while whole-plant fresh weight and leaf length declined by approximately 13% [1]. The study also associated enhanced airflow with hydraulic constraint, growth reduction and tip burn. The central issue is therefore the balance between insufficient exchange under still conditions and excessive local demand under stronger or poorly distributed air movement [4].

## II. Background and Scope

Leaf exchange is influenced by multiple environmental conditions, which can obscure the specific role of air movement. Research on diffuse light demonstrates that radiation distribution within a canopy can influence leaf temperature, but it does not establish the boundary-layer processes responsible for heat and mass transfer around leaves [5]. Light remains relevant because it contributes to leaf energy balance and photosynthetic activity. However, explaining an airflow response by reference to light alone would conflate two distinct processes. The present discussion therefore focuses on the resistance to exchange adjacent to leaves and on the consequences of altering that resistance [6].

Broader accounts of soilless cultivation recognise that crop performance depends on water-air balance and growth-environment regulation, alongside nutrient delivery and rhizosphere processes [7]. Such accounts establish the importance of climate conditions but do not directly compare inadequate, excessive or uneven airflow around leaves. This distinction is important because air-related variables may be treated too generally in system descriptions. A leaf boundary layer is a local transport condition, and its significance must be established through evidence connecting leaf-level airflow with heat, water-vapour and carbon-dioxide exchange rather than through general environmental-management claims [8].

Root-zone transport provides a useful contrast rather than direct evidence of leaf airflow effects. Oxygen limitation and spatial gradients in nutrient film systems can impair crop performance, but these processes occur in the root environment and do not establish how air movement changes exchange at leaf surfaces [9]. Both root-zone and leaf processes illustrate the importance of local gradients and transport resistance. Nevertheless, they should not be treated as interchangeable causes of changes in growth, water use or gas exchange. This paper excludes root-zone oxygen management and concentrates on the air immediately surrounding leaves.

## III. Core Concepts and Mechanisms

The leaf boundary layer functions as a resistance within the pathway between leaf tissues and the surrounding air. When air near the surface remains comparatively still, heat and gases must move through that layer before reaching the bulk atmosphere. Air movement can reduce this resistance by renewing the surface air, changing the conditions for heat loss and diffusion. The significance of local gradients is evident in root-zone research, where oxygen limitation and spatial variation affect crop performance [9]. Yet the relevant leaf mechanism is different: the boundary layer concerns the atmospheric path for heat, water vapour and carbon dioxide, not dissolved oxygen transport within the nutrient solution.

Airflow operates alongside temperature, humidity, radiation and carbon dioxide conditions in controlled environments. Reviews of soilless agricultural systems identify airflow and climate control as relevant variables and discuss gas exchange generally, but they do not offer direct experimental evidence for leaf responses to airflow extremes [10]. Direct physiological evidence is consequently required to establish causal interpretation. Reduced boundary-layer resistance may increase the physical potential for exchange, but stomatal responses and leaf water status determine whether that potential is expressed as increased transpiration, maintained carbon assimilation or a constrained response.

The need to distinguish interacting variables is reinforced by lighting research. Light intensity and spectrum affect leaf photosynthetic physiology, yet they do not directly explain boundary-layer heat and mass transfer [11]. Similarly, lighting-design optimisation identifies airflow as an environmental effect that may remain outside optical models and reports trade-offs among photosynthetic performance, uniformity and energy use [12]. These findings support an integrated view of crop microclimate, but they cannot establish a particular airflow response. Claims about air movement must therefore remain anchored in studies that measure leaf-level exchange under changed airflow conditions.

## IV. Evidence Synthesis

The strongest accepted evidence comes from sustained low-airflow comparisons in lettuce. A change from 0.22 to 0.65 m s$^{-1}$ modified the leaf-surface microclimate and elevated transpirational demand. Stomata responded dynamically by closing, with an associated increase in intrinsic water-use efficiency [1]. This result demonstrates that reduced boundary-layer resistance does not yield a simple linear improvement in gas exchange. Plant regulation mediates the response because the need to limit water loss can constrain carbon dioxide uptake. Air movement consequently changes transpiration, cooling and gas exchange together, but their magnitudes and directions need not be identical.

The same evidence reports that stomatal closure did not fully compensate for greater water loss and that photosynthetic limitation occurred on the adaxial leaf side, indicating spatially differentiated diffusion conditions around the leaf [1]. This observation is consistent with the boundary-layer concept because a leaf does not experience the surrounding environment as a uniform air volume. At the whole-plant scale, increased airflow was associated with reduced fresh weight and leaf length, showing that short-term leaf-exchange responses may be linked to longer-term acclimation and growth [1]. However, the findings should not be treated as universal airflow thresholds because they derive from particular crops and tested conditions.

Related studies define important limits to attribution. Controlled-environment modelling can examine vapour pressure deficit, temperature, transpiration, cooling and dehumidification while assuming airflow rather than experimentally varying it [13]. Research on rising vapour pressure deficit also connects leaf-to-air water demand with stomatal conductance, transpiration, photosynthesis and leaf temperature, but does not establish airflow as the causal driver [14]. These sources explain why humidity and temperature remain important context. They also show why direct manipulation of air movement is necessary before a response can be attributed specifically to altered boundary-layer resistance.

## V. Practical Implications and Limitations

The available evidence supports a balanced account of insufficient and excessive airflow. Under relatively still conditions, the boundary layer resists heat and mass transfer around leaves, limiting exchange with the surrounding air [1]. Greater air movement can reduce that resistance, but the same evidence shows that it can increase evaporative demand, induce stomatal closure and increase water loss [1]. The practical implication is not a universal airflow prescription. Instead, air movement should be treated as a modifier of the local conditions in which leaves regulate water loss, cooling and carbon gain, with the response dependent on the wider leaf microclimate.

Poorly distributed air movement warrants similar caution. Controlled-environment literature identifies airflow uniformity and the diffusion of moisture and carbon dioxide as relevant concerns, although it supplies limited direct physiological evidence comparing uneven airflow patterns [15]. Direct lettuce evidence shows that airflow responses can differ across leaf surfaces, but it does not establish the consequences of every possible canopy distribution pattern [1]. Thus, uneven airflow may create unequal local boundary-layer conditions, but crop-specific performance effects require direct validation. Nominally uniform environmental set points should not be presumed to imply uniform leaf exposure.

Several evidence limitations constrain broader generalisation. Aeroponic research shows that root-zone oxygen availability and gas exchange affect plant performance, but it does not test airflow-driven changes in leaf temperature, transpiration or photosynthesis [16]. General mass-transfer research also shows that transfer conditions and temperature influence oxygen dissolution in water, but it does not describe leaf boundary layers [17]. These studies support the wider importance of gradients and transport resistance, yet neither can substitute for direct leaf physiological evidence. Future

validation should measure local airflow, leaf-surface conditions, stomatal behaviour and growth while separating airflow effects from concurrent climate variation.

## VI. Conclusion

Air movement around leaves changes transpiration, cooling and gas exchange because it alters the boundary layer that resists heat and mass transfer at the leaf surface. Direct evidence demonstrates effects on boundary-layer conductance, leaf temperature, transpiration, stomatal regulation, photosynthesis and growth [1]. The physiological outcome is conditional rather than uniformly beneficial: reduced resistance can promote exchange, whereas excessive evaporative demand can increase water loss, trigger stomatal closure and constrain growth [1]. This relationship explains why both relatively still air and excessive or poorly distributed air movement can create plant-performance problems.

The highest-value next work is controlled leaf-level research that separates airflow effects from concurrent changes in vapour pressure deficit, temperature, radiation and crop architecture. Existing controlled-environment analyses recognise these interacting conditions but often assume airflow rather than experimentally varying it [13]. Measurements that connect local air movement with leaf-surface microclimate, stomatal response and growth would provide stronger evidence for interpreting boundary-layer processes across crop systems.


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