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Short communication

Modelling to determine the optimal porosity of shelterbelts for the capture of agricultural spray drift

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ABSTRACT

Shelterbelts are not only useful as windbreak protection for stock and crops but can also be used to capture spray drift and reduce the spread to non-crop areas with important environmental consequences. The porosity of a shelterbelt can significantly influence the ability to capture spray drift. The aim of this work is to determine the optimal shelterbelt porosity that maximises spray drift capture. This has implications to future shelterbelt plantings and species selection. Here a model is developed for the flow through and over a shelterbelt. This model is used in conjunction with a spray capture model to determine the capture efficiency of shelterbelts with different porosities. Values of the optical porosity between 10% and 40% are found to give the best capture efficiency over a range of shelterbelt structures with the optimum generally around 25%. It is hoped that in the future experimental validation of these models will be undertaken. This will further enhance the understanding and use of shelterbelts as spray mitigation devices.

1. Introduction

Shelterbelts or windbreaks are used in many ways in agriculture, forestry and environmental protection. The most common usage is to protect downwind crops and livestock by reducing the wind velocity on the lee side of the shelterbelt. Windbreaks are also important tools in erosion control (Funk et al., 2004; Gregory et al., 2004; Ticknor, 1988) and provide many benefits to wildlife by providing shelter, refuge cover, foraging sites, reproductive habitat and travel corridors (Johnson and Beck, 1988).

Another important, and often overlooked, function of shelterbelts is the interception and capture of agricultural spray drift. While there has been some research on spray drift reduction immediately behind a porous shelterbelt there is substantially less work on the total reduction in spray drift from both the through shelterbelt drift and the over shelterbelt drift. Experimental results using both fluorometric and droplet counting methods show that reductions in spray drift of up to 80–90% immediately behind a porous shelterbelt are possible (Raupach et al., 2001; Ucar and Hall, 2001). Unfortunately this is only the reduction in the drift that passes through the shelterbelt and does not take into account the drift that is forced up and over the shelterbelt.

Spray drift capture by shelterbelts can reduce the spread to non-crop areas with important environmental consequences, hence it is important to model and understand the potential benefits of this capture. This modelling work will further enhance the understanding and use of shelterbelts as spray mitigation devices.

For spray drift capture the two most important features of a shelterbelt are the porosity of the shelterbelt, as this determines the velocity of the wind through the shelterbelt, and the vegetation element size within the shelterbelt, as this determines the capture efficiency of the vegetation. Consider the case of a shelterbelt with an incoming air velocity perpendicular to the shelterbelt. A very dense shelterbelt will inhibit the flow of air through the shelterbelt hence the majority of the incoming air is deflected up and over the shelterbelt carrying any spray drift with it up and over the shelterbelt to be deposited farther downwind. A very porous shelterbelt does not overly impede the air flow but also does not have enough vegetation elements to capture the spray drift and so the majority of the drift will pass through the shelterbelt uncaptured. There is a porosity range that will provide the optimum spray drift capture. Very little experimental work on determining this optimal range with the limited previous work suggesting values in the range of 25% to 40% depending on the structure of the shelterbelt (Schwartz et al., 1995; Ucar and Hall, 2001).

The droplet size distribution in the spray drift is an important consideration for drift and capture calculations. For a typical spraying scenario, droplets with a diameter of the order of 100 μm or larger settle out of the flow in a timescale shorter than the times scales for the flow and are also very efficiently captured. Droplets less than 10 μm in diameter are highly unlikely to be captured and

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are also susceptible to evaporation (Anonymous, 2002; Mercer and Roberts, 2005). Hence, we can limit our investigation to droplets in the range 10–100 μm in diameter.

Here we calculate the flow through and over a shelterbelt and use this flow to determine the total capture efficiency of the shelterbelt. This is model is then run numerous times to determine the optimal porosity that maximises the shelterbelts capacity to intercept spray drift.

2. Mathematical models

The model developed here for spray drift capture by a shelterbelt consists of two distinct parts; a flow model and a capture model. The assumption here is that the spray drift under consideration is carried along by the flow which is influenced by the presence of the shelterbelt.

2.1. Flow model

The accurate numerical modelling of flow through and over a porous shelterbelt is a difficult and computationally expensive undertaking (Plate, 1971; Wang et al., 2001). Many factors must be taken into account such as turbulence effects, varying drag in the shelterbelt with different sized and orientated vegetation elements, boundary layers and streamlining of vegetation. We do not develop an all inclusive flow model but rather present a model that captures the main features of deflection over the shelterbelt and reduced air flow through the shelterbelt. Provided the flow model has these basic features it will be of use in determining the optimal porosity for spray drift capture.

We use a model with a steady uniform horizontal air velocity, U, well upstream of the shelterbelt. The ambient wind velocity is assumed to be perpendicular to the shelterbelt so a two dimensional model is appropriate. The shelterbelt is modelled as a region of high drag according to the quadratic drag law (drag increases with the square of the velocity) which is appropriate for the velocities and vegetation elements under consideration (Fang and Wang, 1997). The governing equations for a relatively simple steady state eddy viscosity model of mean turbulent flow are

$$\rho_a(\boldsymbol{u}\cdot\nabla\boldsymbol{u}) = -\nabla p + \nabla\cdot(\rho_a \nu \nabla \boldsymbol{u}) - \frac{1}{2}C_D\rho_a\boldsymbol{u}|\boldsymbol{u}| \quad (1)$$

$$\nabla\cdot\boldsymbol{u} = 0 \quad (2)$$

where $\boldsymbol{u}$ is the two dimensional velocity vector, p the pressure, ρ_a the air density and ν is a turbulent eddy viscosity (both assumed to be constant). C_D is the drag coefficient which is taken as unity in the shelterbelt and zero elsewhere. This is a reasonable assumption over the range of velocities, vegetation element sizes and porosities typically found experimentally in a shelterbelt (Grant and Nickling, 1998).

2.2. Capture model

The capture efficiency of a porous shelterbelt depends on the wind bleed velocity through the shelterbelt, spray drift droplet size, size of the shelterbelt vegetation elements and overall porosity of the shelterbelt. The wind velocity through the shelterbelt is obtained using the above flow model. Droplet size is important since as fluid flows around a vegetation element small spray drift particles are swept up with the flow while larger particles with more inertia will deviate from the flow and possibly impact on the vegetation and be captured, see Fig. 1.

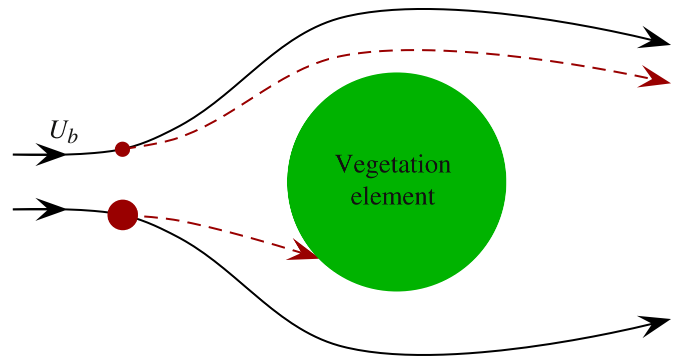

Fig. 1. Large spray drift particles are carried by their inertia into vegetation elements and captured whereas lighter particles more closely follow the flow and may not be captured.

Peters and Eiden (1992) derived an empirical formula for the efficiency, E, of the capture by an individual vegetation element as,

$$E = \left(\frac{St}{St + 0.8}\right)^2, \quad (3)$$

based on the Stokes' number of the flow, $St = \rho_p d_p^2 U_b / 9\rho_a \nu_a d_e$ where U_b is the bleed velocity, ρ_p is the density of the droplet, d_p the diameter of the droplet, ρ_a the density of the air, ν_a the kinematic viscosity of air and d_e the diameter of the vegetation element. Evergreen species with needle vegetation (such as pine) would be expected to be better at capturing spray drift than broadleaf vegetation (such as poplar) and this has been verified experimentally by Ucar et al. (2003). Also, since the larger droplets have greater inertia they also have higher capture efficiency. Higher bleed velocity through the shelterbelt also leads to higher capture efficiency as the droplets have less time to deviate around the vegetation elements.

The aerodynamic porosity of a shelterbelt has a dramatic effect on its ability to capture spray drift (Ucar and Hall, 2001). Unfortunately the aerodynamic porosity of a shelterbelt is often difficult to determine and is generally not a useful quantity to consider for field measurements. A more common measure of porosity is the optical porosity (τ) which can be estimated by simple visual techniques or from photographs (Schwartz et al., 1995). Optical porosity is therefore a better parameter to use as it is measurable in the field and hence more easily incorporated in to spray drift mitigation software that require field data inputs. Raupach and Lu (2004) give a relationship linking the aerodynamic porosity and the optical porosity. This is then used to calculate the total capture efficiency, T, for a given optical porosity, τ, as

$$T = 1 - \tau^{EM} \quad (4)$$

where M is a meandor factor allowing for turbulence in the shelterbelt and is taken as 1.2. This relationship is valid except in the limit as τ tends to zero (very dense shelterbelts) since as the optical porosity tends to zero the aerodynamic porosity does not necessarily reduce to zero. The capture efficiency, E, given in Equation (3), varies with the bleed velocity through the shelterbelt so by integrating the efficiency of the capture over the shelterbelt it is possible to determine the total capture efficiency of the shelterbelt.

2.3. Materials and method

The governing equations for the flow (1) and (2) are solved using a commercially available time and space adaptive finite element package FlexPDE (2007). Once this flow is found for a given