Spatial structure and evolution in emergent vegetated ecosystems

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I. Introduction – recent experiments on flow-biogeomorphic feedbacks

Motivation: Recent losses of mangroves, seagrasses, and coastal marshes have increased the need to restore these aquatic environments[1,2,3,4], which are important for their inherent value as habitats[4], benefit in erosion protection[2], and high capacity as atmospheric carbon sinks[3].

Background: The small-scale hydrodynamics governing sediment-vegetation interactions may determine optimum transplantation techniques for restoration[4]. Recent field and experimental studies show that both the wakes behind individual patches of aquatic vegetation as well as the interaction of neighboring patch wakes may play an important role in the evolution of vegetation[5,6] (Figure 1), an effect not captured in current landscape evolution models.

Objective: To incorporate the flow-biogeomorphic interactions at the patch scale shown in Figure 1 into a simple model for vegetation development, and to evaluate their importance to landscape evolution by varying the initial density of the simulation (*ID*) and the sediment motion threshold velocity (*TV*).

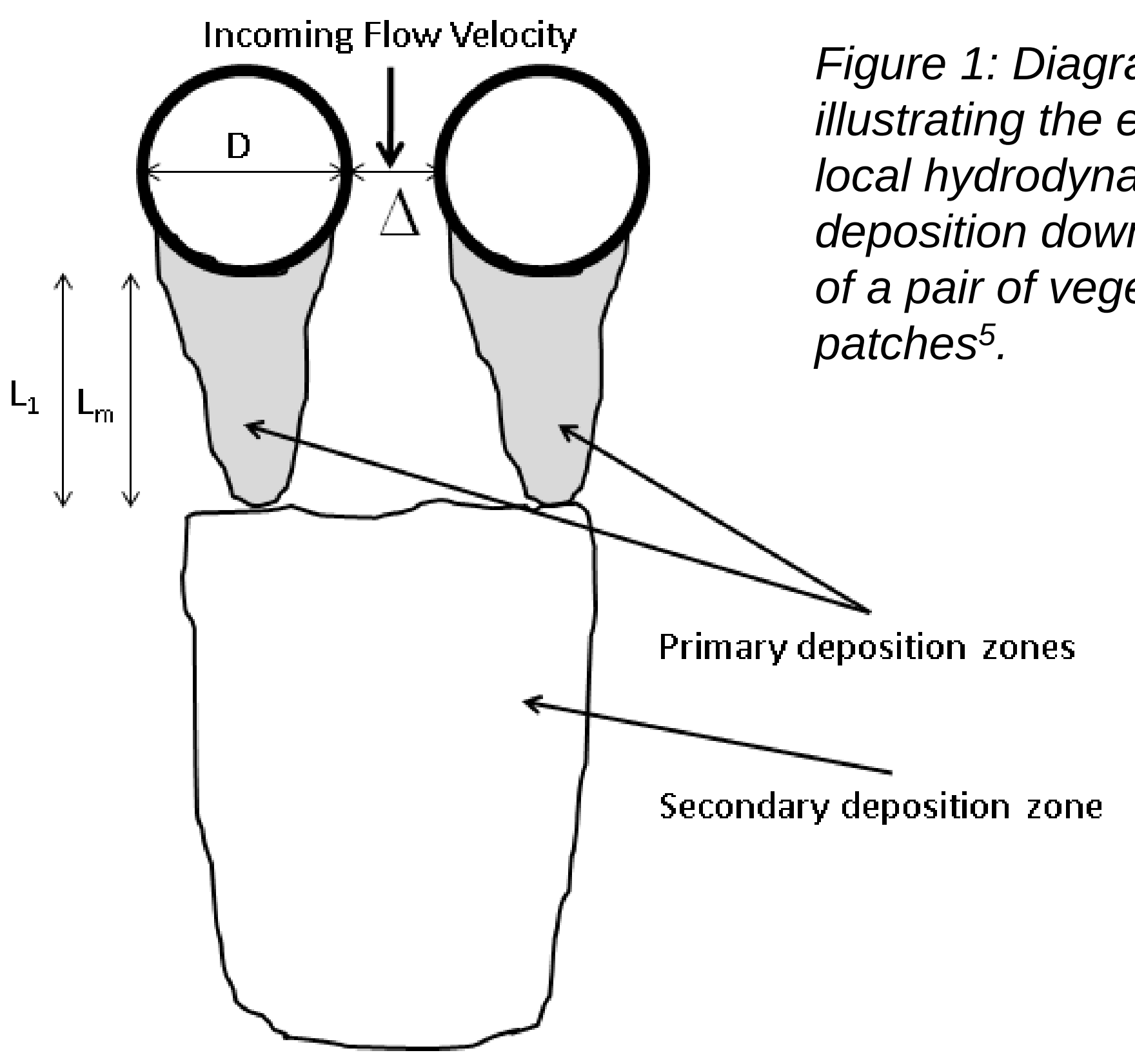

Figure 1: Diagram illustrating the effect of local hydrodynamics on deposition downstream of a pair of vegetation patches[5].

II. Methods – a scaled model for landscape evolution

Vegetation growth is positively correlated with deposition, and deposition is linked to velocity as shown in Figures 2 and 3.

1. Model initialized by random vegetation patch placement at initial density *ID*. Patches present high resistance to flow, whereas areas of bare bed have low resistance to flow.
2. MODFLOW solves for the distribution of hydraulic heads
3. Velocity in each cell calculated from spatial gradient in head
4. Velocity field modified to account for the effects of wakes
5. Matlab updates the vegetation landscape probabilistically (Figure 3)
6. Simulation terminates when domain growth is less than 0.5%

$$\cancel{U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}}=-g\frac{\partial H}{\partial x}-C_dU+\cancel{\nu_t\left(\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}\right)}$$

$$\cancel{U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}}=-g\frac{\partial H}{\partial y}-C_dV+\cancel{\nu_t\left(\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}\right)}$$

$$\Rightarrow \left.\begin{aligned} U&=-K\frac{\partial H}{\partial x}\\ V&=-K\frac{\partial H}{\partial y}\end{aligned}\right\} \quad \frac{\partial}{\partial x}K\frac{\partial H}{\partial x}+\frac{\partial}{\partial y}K\frac{\partial H}{\partial y}=0$$

MODFLOW efficiently solves a potential flow problem, and viscous wake effects are added back in Matlab

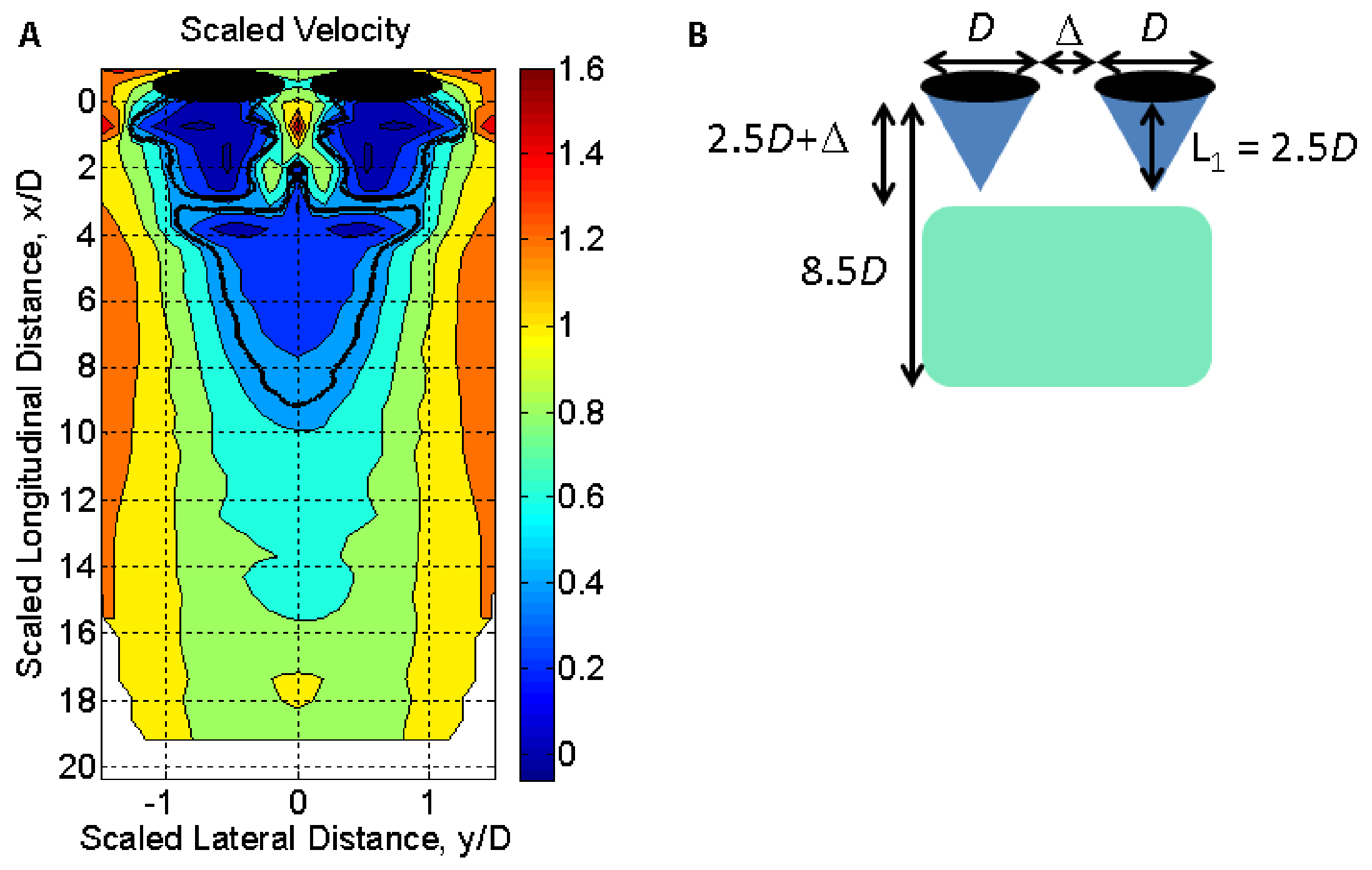

Figure 2: (**A**) Measured velocity field[5] around two patches scaled by the far upstream velocity, U_0. The heavier contour marks the isovel 0.5U_0. (**B**) A diagram of the wake modifications made to the velocity field after each MODFLOW calculation. The near wake zone extends a distance L_1 = 2.5*D* from each patch (shown in blue). In this zone the velocity was reduced to 20% of the MODFLOW calculated value. Within the secondary deposition zone (shown in green) the velocity was reduced to 50% of the local MODFLOW value.

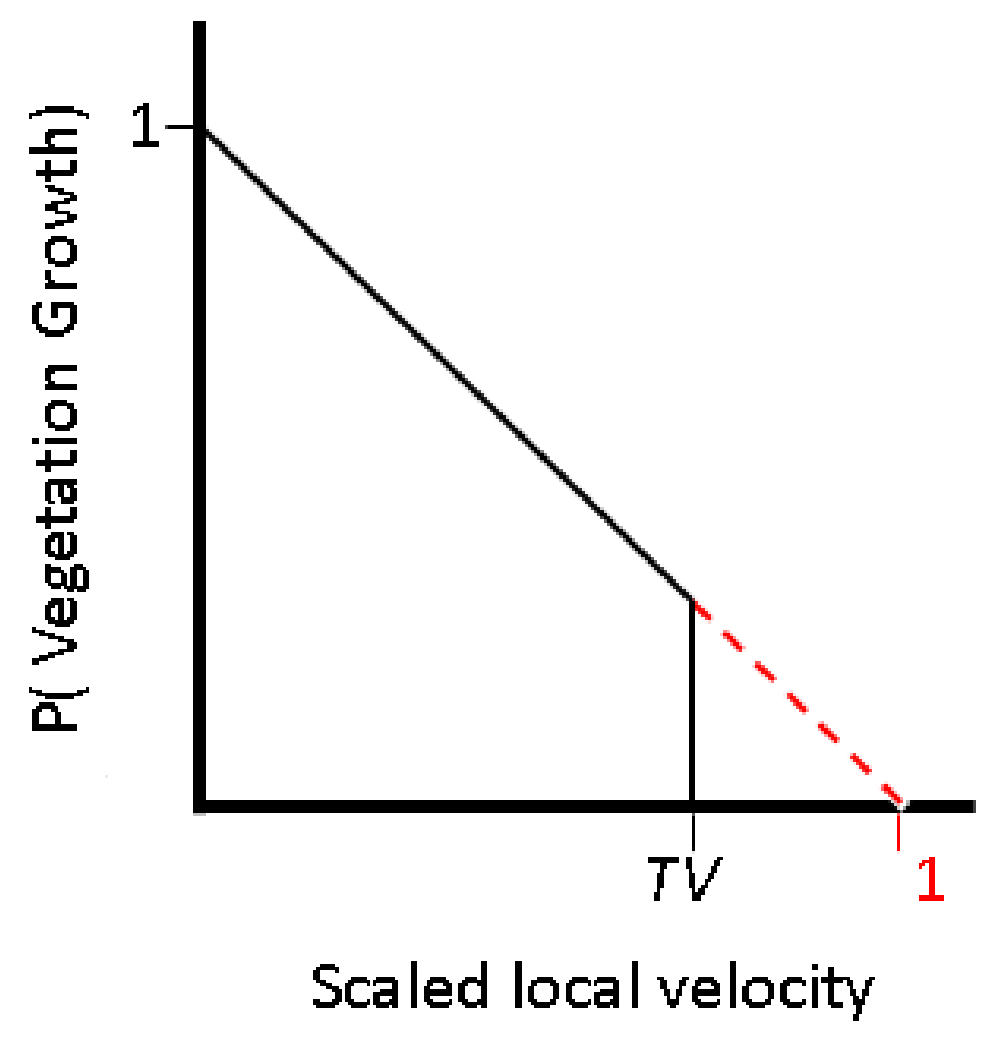

Figure 3: Probability distribution governing likelihood of vegetation growth at a cell based on the local velocity field.

III. Results – realistic outcomes and *ID*, *TV* dependencies

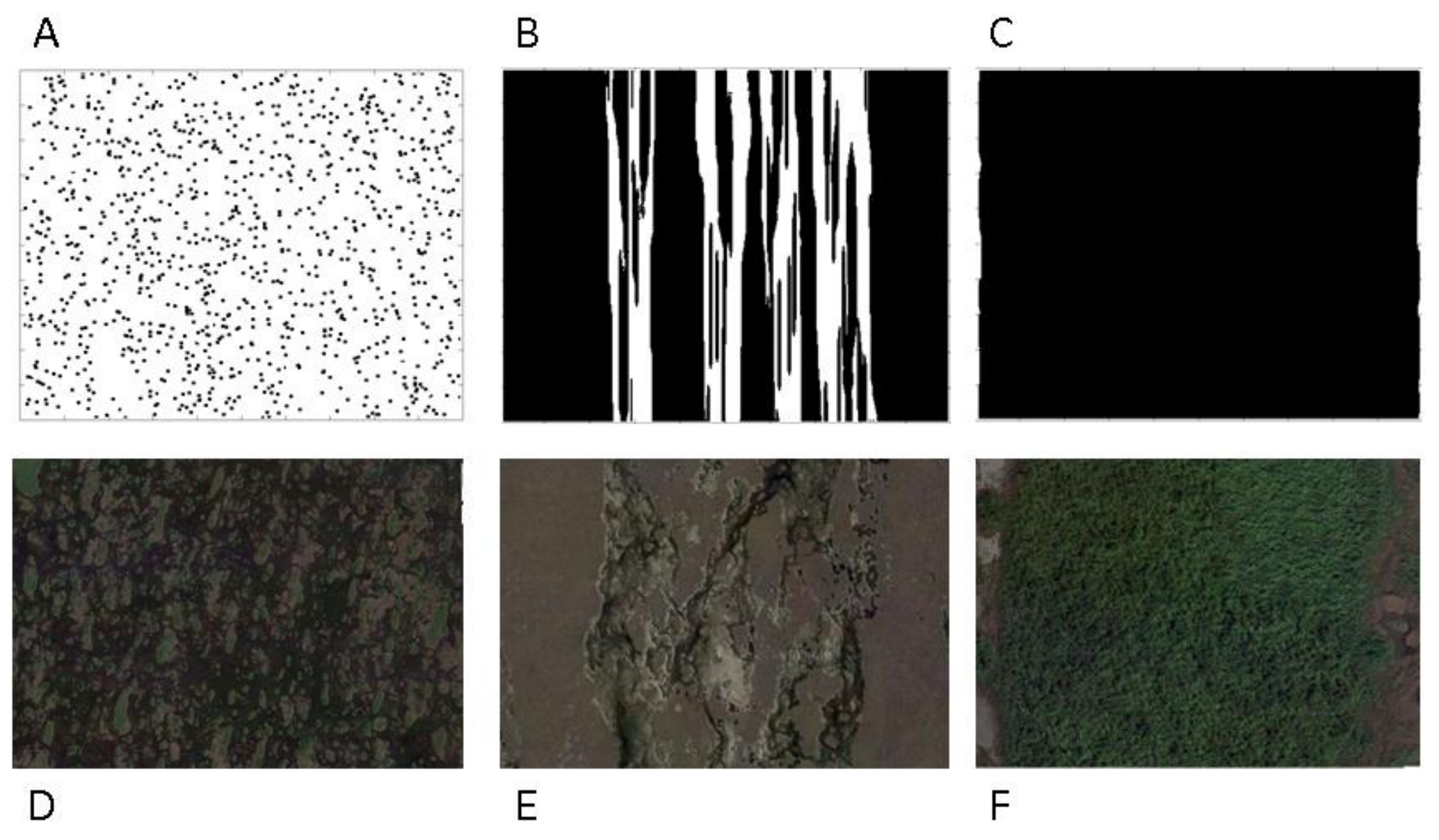

Figure 4: (A) sparse, (B) channeled, and (C) filled simulation end-states ID = 4% *for each case, with* TV = 0, 0.1, and 0.7, *respectively. Examples from the Florida Everglades of landscapes visually classified as (D) sparse, (E) channeled, and (F) filled.*

ID \ *TV*	0	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.07	S	S	S	S	S	**S**	S	S	S	S	**C**	F
0.09	S	S	S	S	S	S	S	**S**	S	S	**C**	F
0.4	S	S	**S**	S	S	**S**	S	**S**	**S**	**C**	F	F
0.9	S	S	**S**	**S**	S	**S**	S	**S**	**C**	**C**	**F**	F
1.8	S	**S**	**S**	**C**	C	**C**	C	**C**	C	**C**	F	F
3.3	S	**C**	**C**	C	**C**	**C**	**C**	**F**	F	F	F	F
3.5	S	C	C	**C**	**C**	**F**	F	**F**	F	**F**	F	F
4.3	S	**C**	**F**	**F**	F	**F**	F	**F**	F	**F**	F	F
5.2	S	**F**	F	F	F	F	F	F	F	F	F	F
6	S	F	**F**	**F**	F	**F**	F	F	F	F	F	F

Figure 5: Summary of the simulation outcomes at different values of ID *and* TV. *Sparse, channeled, and filled outcomes are indicated by S, C, and F, respectively. Bold, underlined letters indicate simulations that were run to completion.*

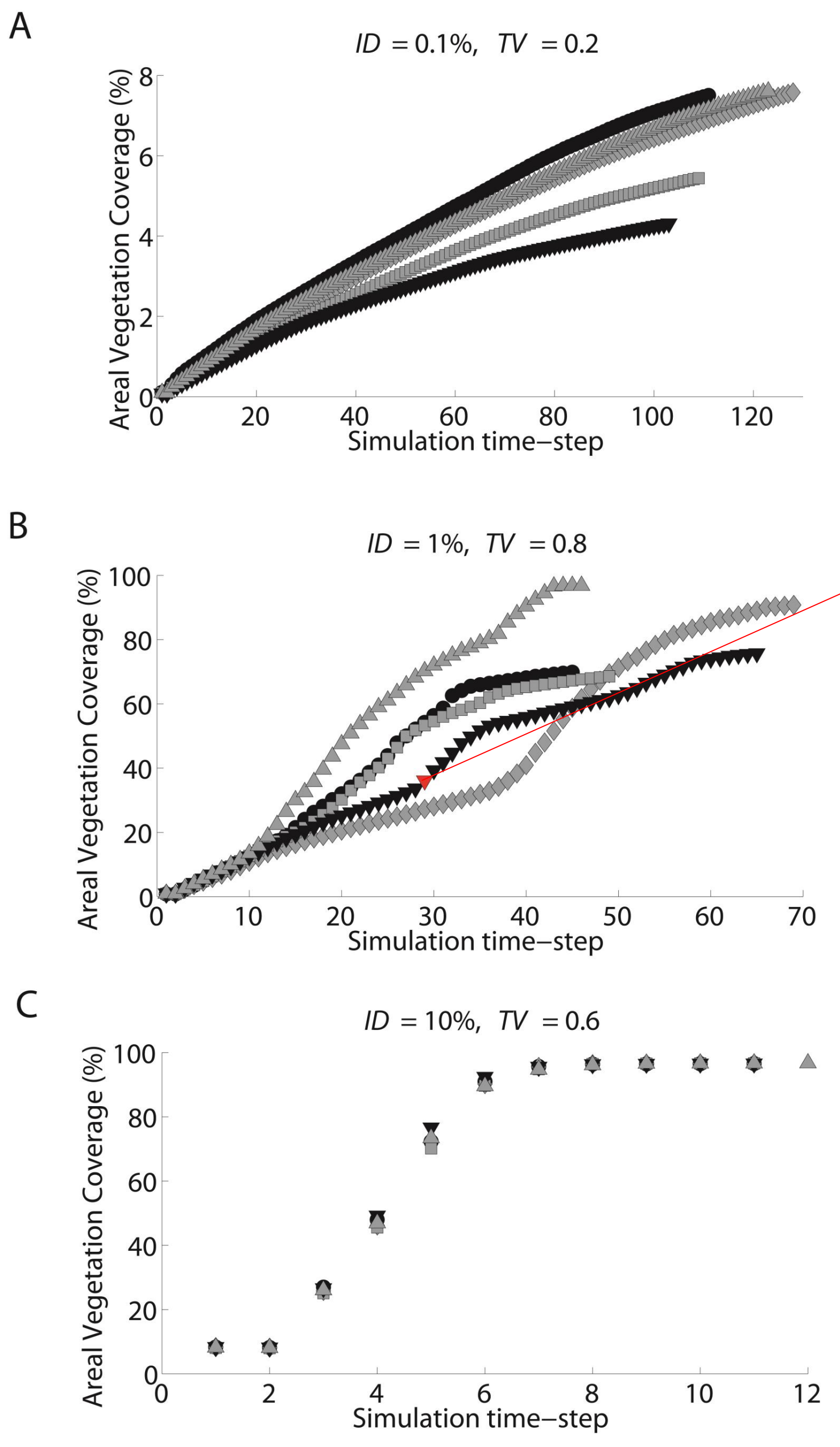

Figure 6: (A) sparse, (B) channeled, and (C) filled growth patterns for the same ID, TV *under 5 random initial patch location configurations, indicated by the 5 different symbols. In (B), time-step 29 is highlighted in red.*

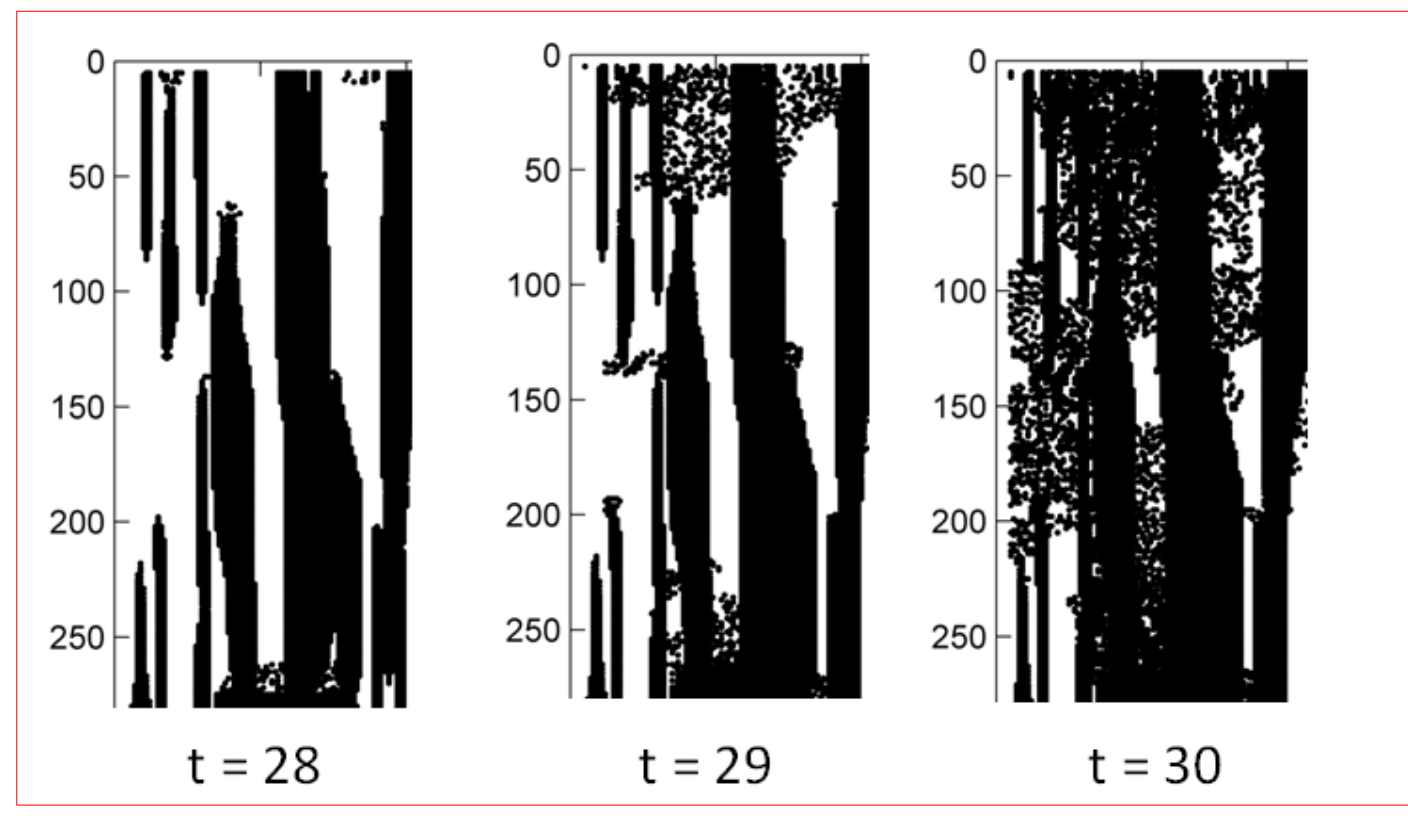

Figure 7: Vegetation growth in a subsection of the flow domain for the inverted triangle case in Figure 6B, ID = 1% TV = *0.8. Vegetation is black and the bare region is white.*

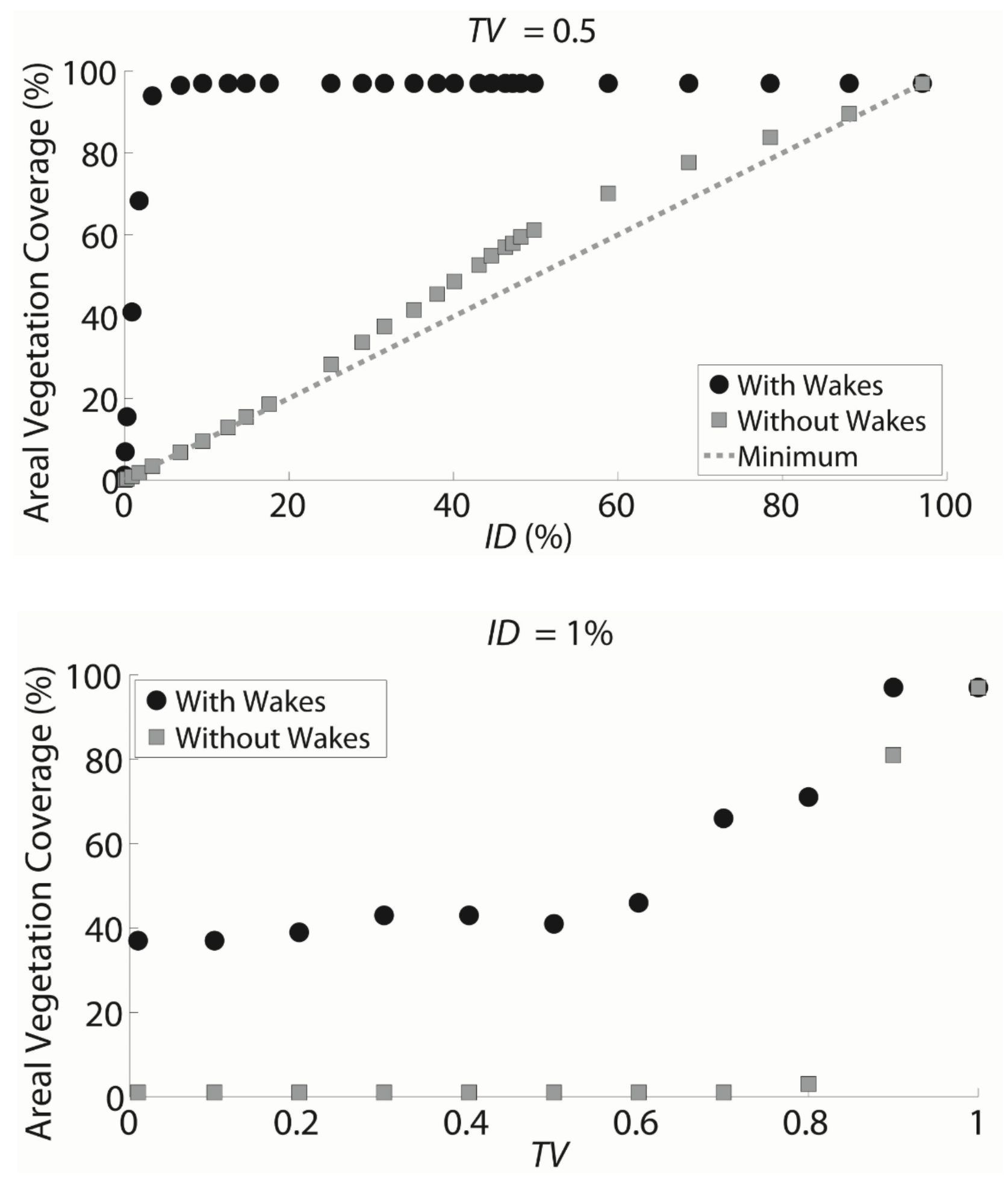

Figure 8: Above, final vegetation density as a function of ID *at* TV = 0.5. *Below, final density as a function of* TV, *at* ID = 1%.

IV. Conclusions and future work – feedbacks in more complex models

- Role of flow diversion in promoting vegetation growth is important at many scales:
  - At the patch scale, flow diversion reduces velocity in patch and in wake, leading to streamwise growth
  - At larger scales, flow diversion into channels stabilizes vegetated regions adjacent to the channels
  - At regional scale, flow diversion encourages growth throughout entire domain
- Channels can be defined by differences in vegetation cover in addition to traditional definitions based on flow depth
- Future work could guide restoration efforts toward utilizing patch-scale hydrodynamics (ideal *ID*), and additional simulations testing deposition implications of different patch configurations are in progress

V. Acknowledgments and references

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