Mechanisms of establishment of bacterial colonies in the rhizosphere

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Roots interact with many soil biological organisms in soil

- Good guys

  Nitrogen fixing

  AM Fungi, P acquisition

  Growth promoting bacteria

  siderophores producing bacteria

  …

Roots interact with many soil biological organisms in soil

- Bad guys

  Nematodes feeding on roots

  Insects feeding on roots

  Parasitic fungi, pathogens

  …

Multiple factors affect bacterial colonisation of the root

- Bacterial species
- Root growth rate
- Soil physical properties
- Root secretion and exudates
- Root morphology
- Sensing / chemotaxis
- Attachment
- Proliferation

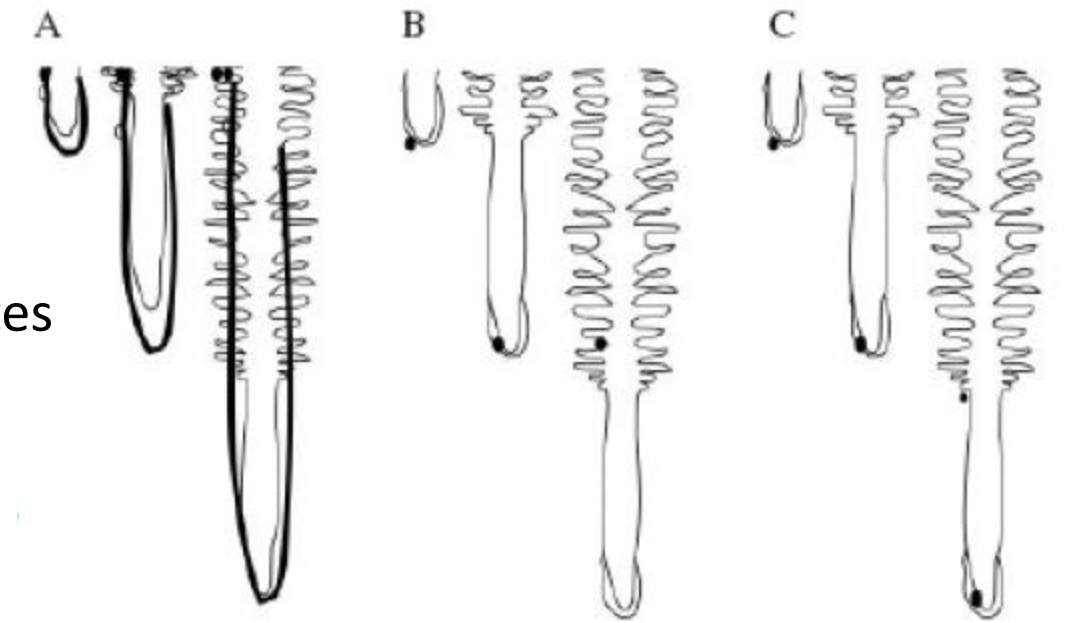


FIG. 5. Diagram illustrating scenarios possible between a growing root and bacteria relatively immobile in the soil. Bacteria are depicted as dark dots; the root tip is shown at three stages relative to the bacteria. (A) Scenario 1: the root tip grows past the bacterium. (B) Scenario 2: the bacterium anchors to the root cap and is carried forward with the tip as it extends (see also Fig. 6). The root cap mucilage is shown as a dark line in (A), suggesting how it covers the root in hard soil, and is shown as a light line in (B), suggesting how it covers the root tip in loose soil (see text for details). (C) Scenario 3: the bacterium swims to main- a particular root developmental zone.

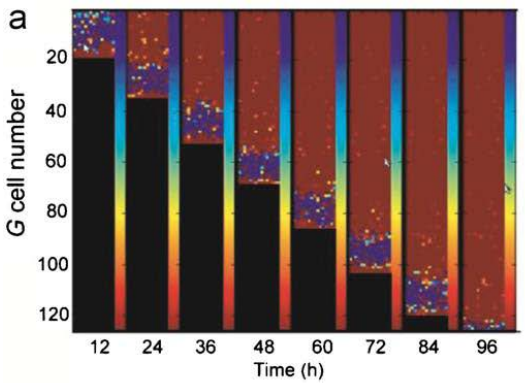
Watt *et al* 2006

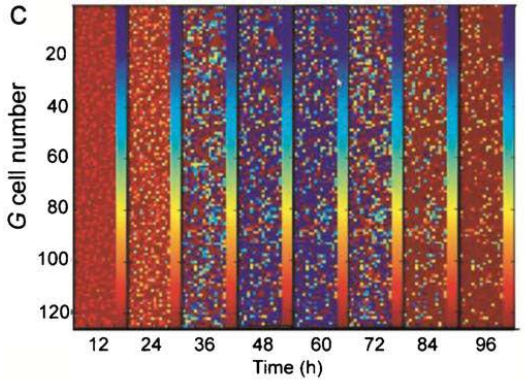
=> What mechanisms?

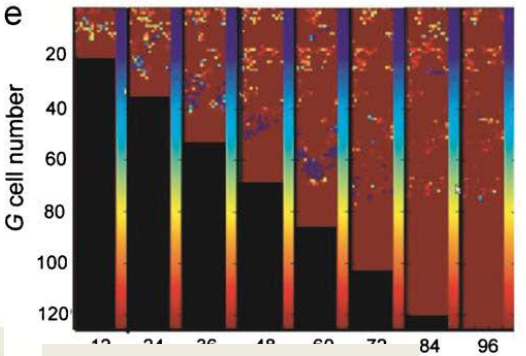
How bacteria colonise roots?

- Source of carbon from the root
- Bacterial growth, mortality
- Mobility, Radial distribution
- Dynamics, competition, oscillations …
- Models describe carbon transport & conservation

- But what's happening at the root tip?







Muci *et al* 2012

Outline

- Observations and current knowledge
- Model of bacterial establishment at the root tip
- What have we learn from the model
- Summarizing

Root exudation contributes to bacterial growth

- Root exude a variety of compounds

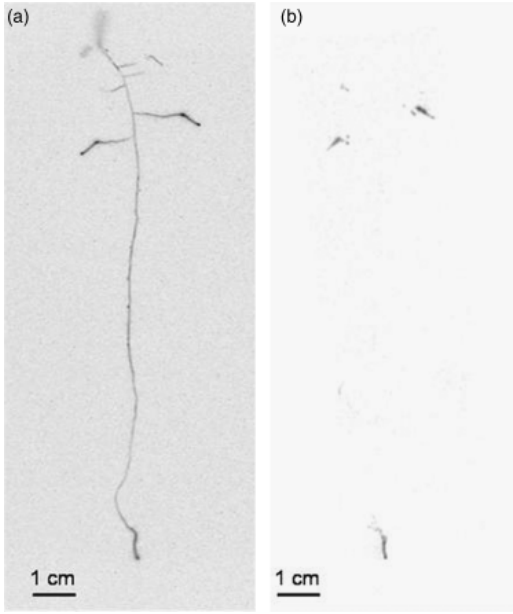
  Mucilage, Organic acids, sugars, amino acids

  Half times: 1h to several days

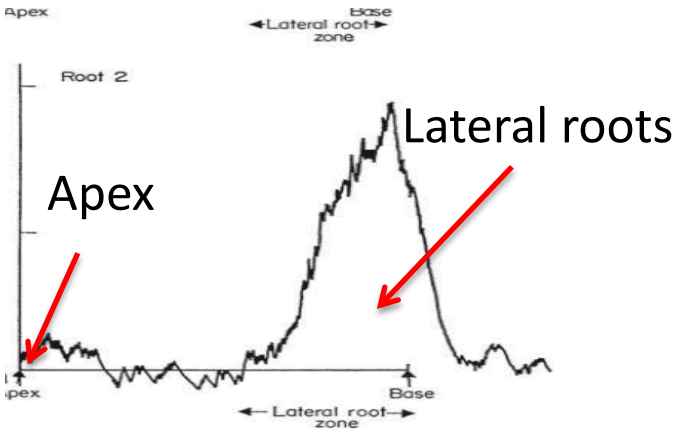
- Bacteria sense, respond and utilise exudates

- There are exudation hot spots

  root tips, intercellular junctions, wounds, lateral root initiation sites



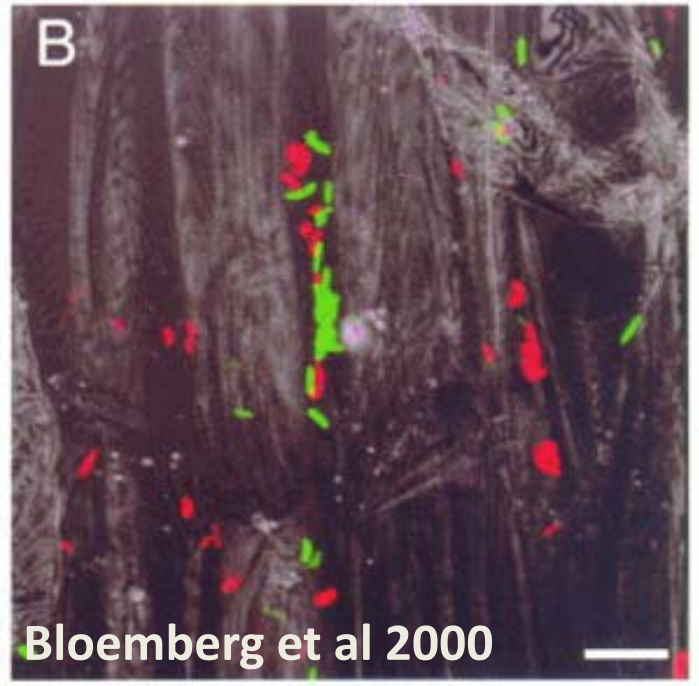
Dennis & Jones (2006)



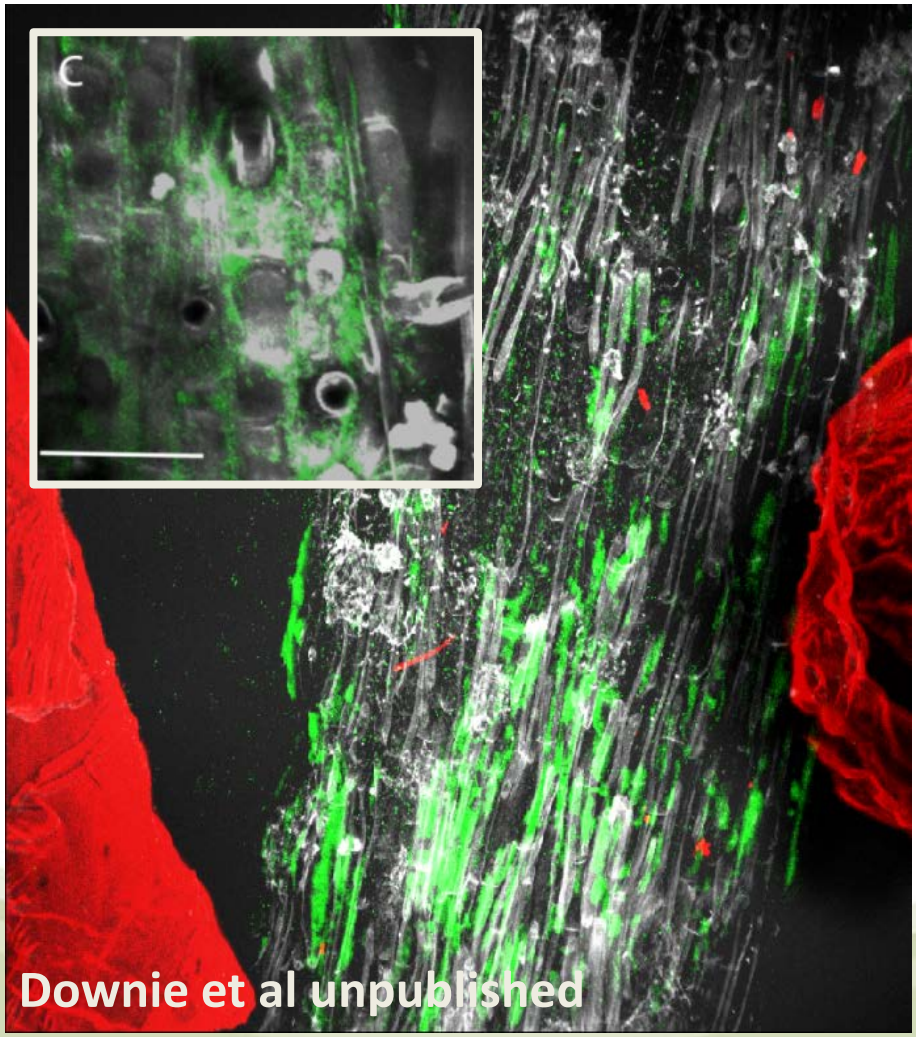
McDougall & Rovira (1970)

Bacteria exploit niches on the root surface

- Lateral root
- Intercellular junction
- Wound



Bloemberg et al 2000



Downie et al unpublished

Bacteria adhere on the root surface to exploit these niches

1. Contact

   Brownian motion / chemotaxis

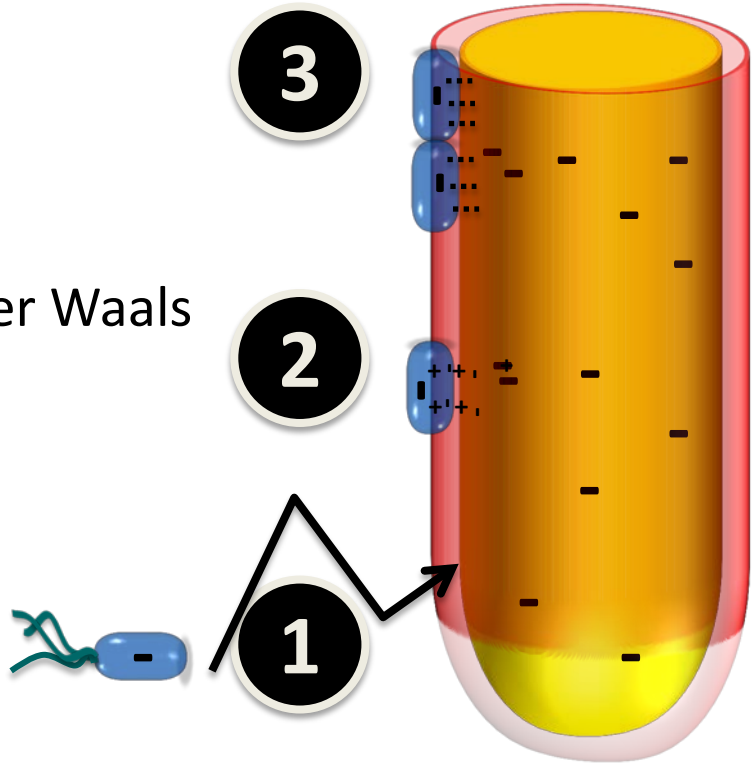
2. Reversible attachment

   + Brownian, chemotaxis, van der Waals

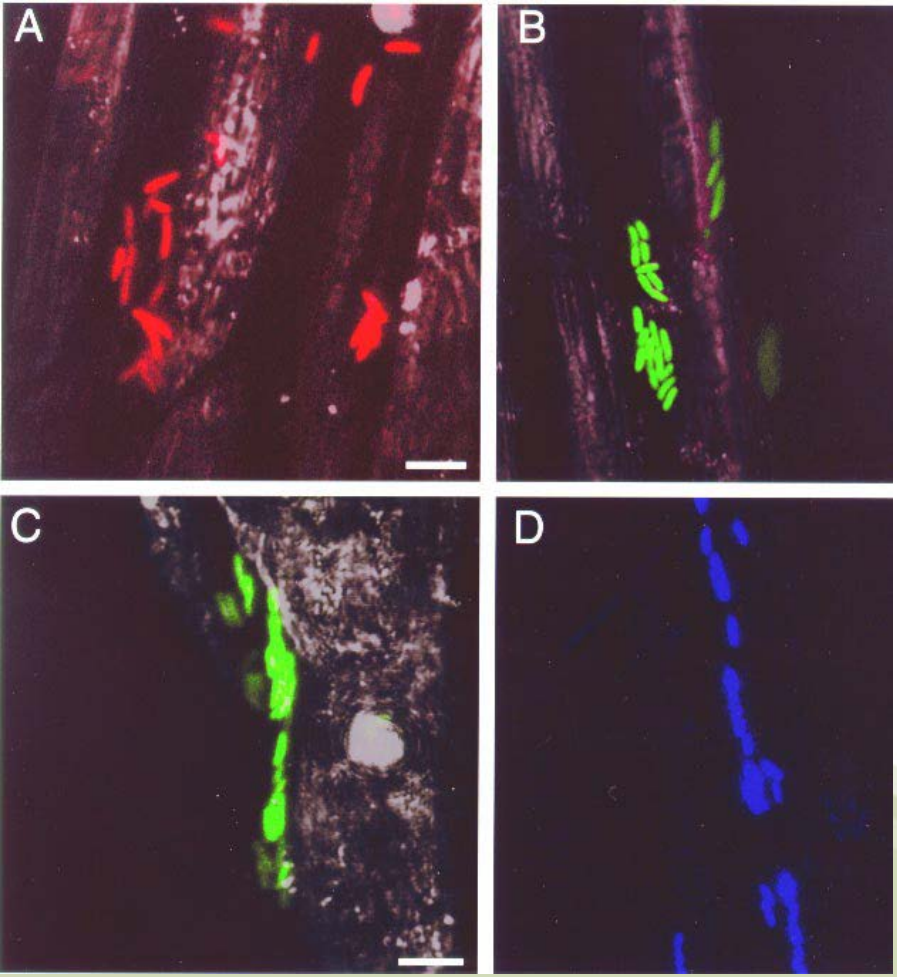
   - Electrostatic

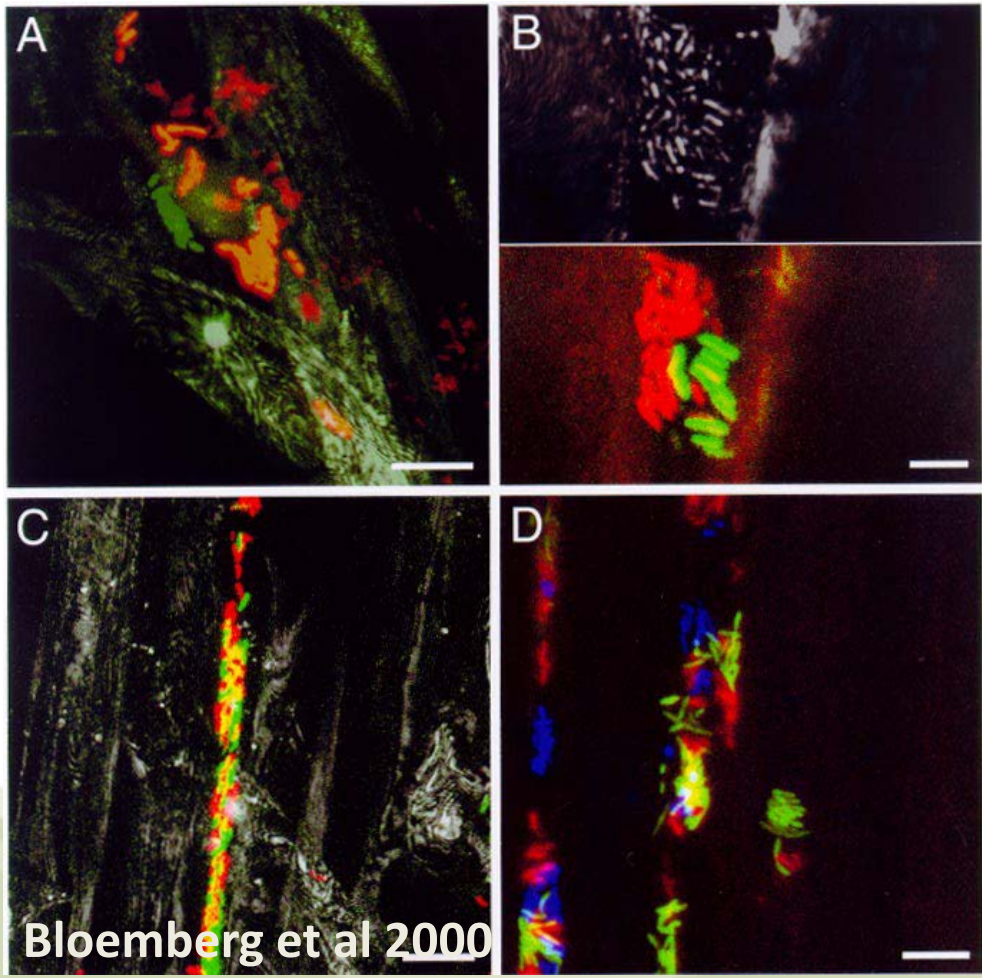
3. Irreversible

   Chemical bounds, Pili, biofilm…



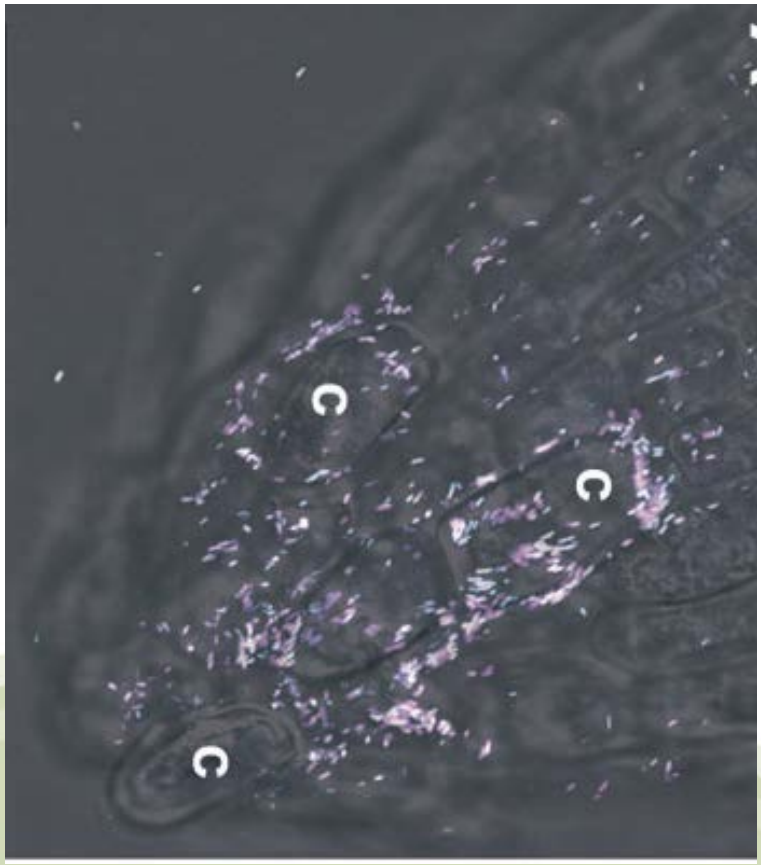
Early attachment is essential



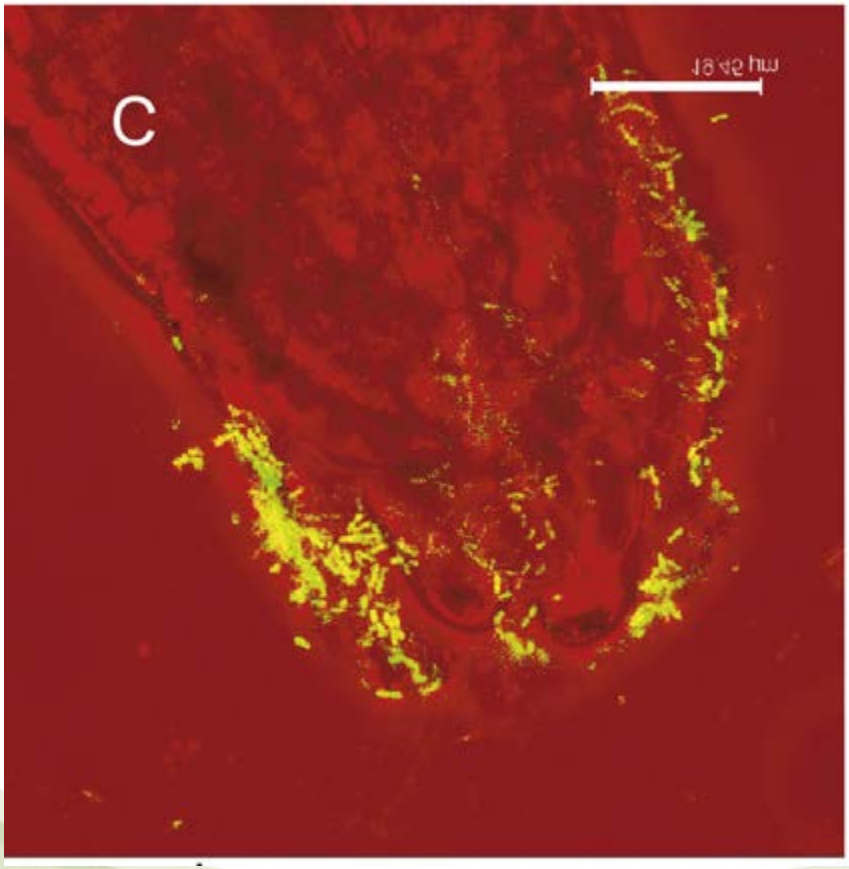


Bloemberg et al 2000

Bacteria may colonise the root tip

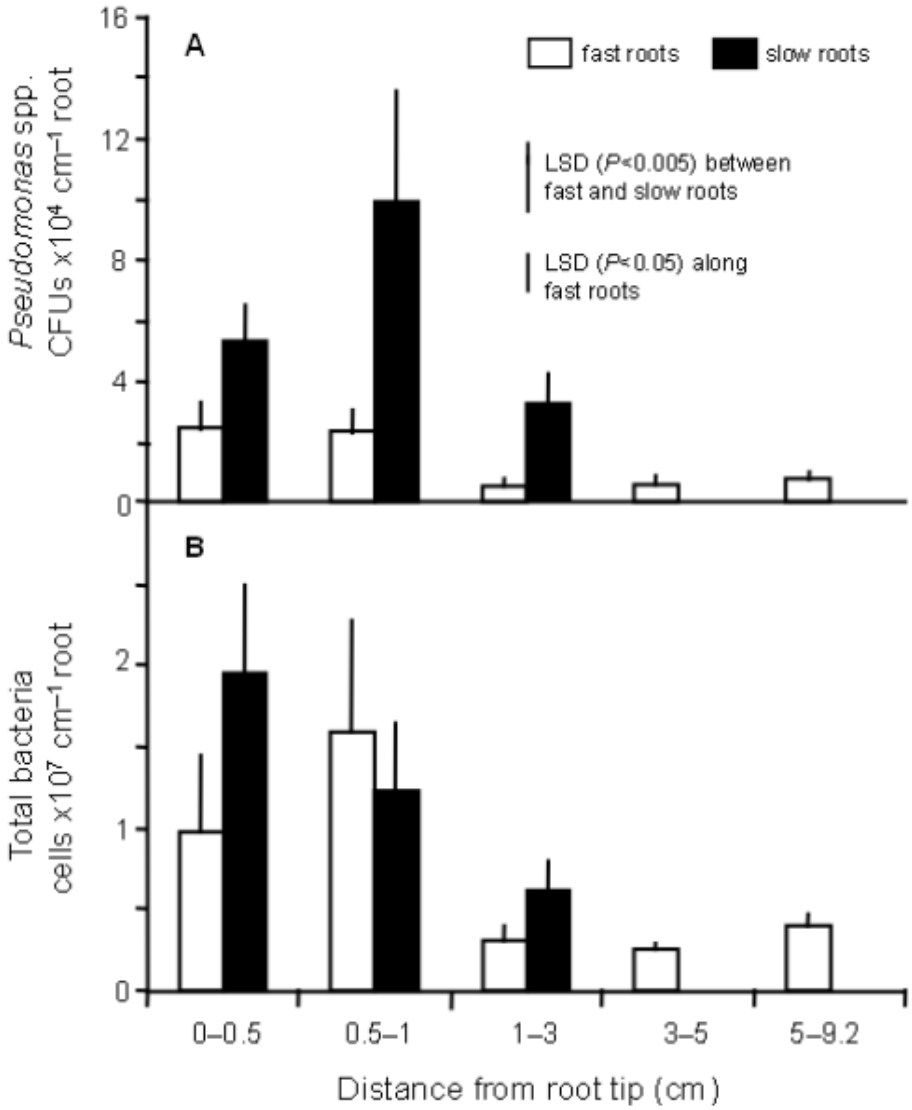


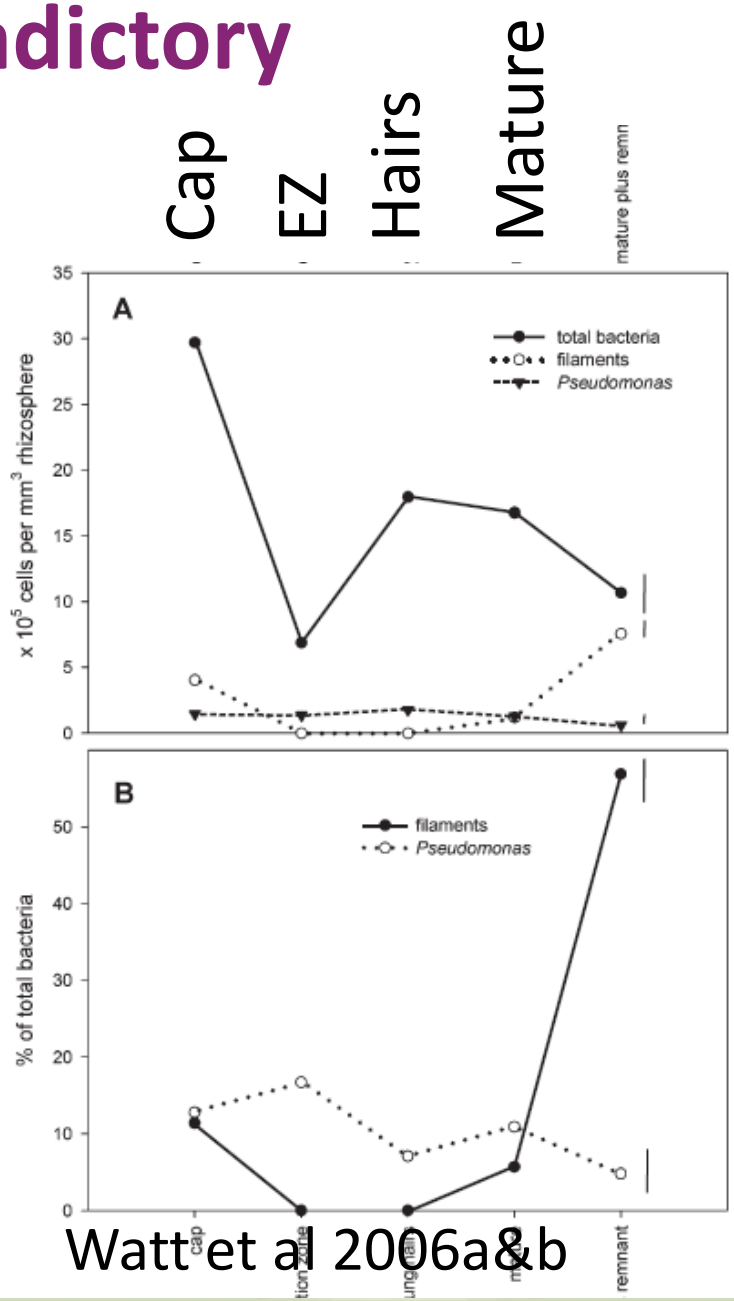
Watt et al 2006 (Barley)



Fan et al 2011 (Arabidopsis)

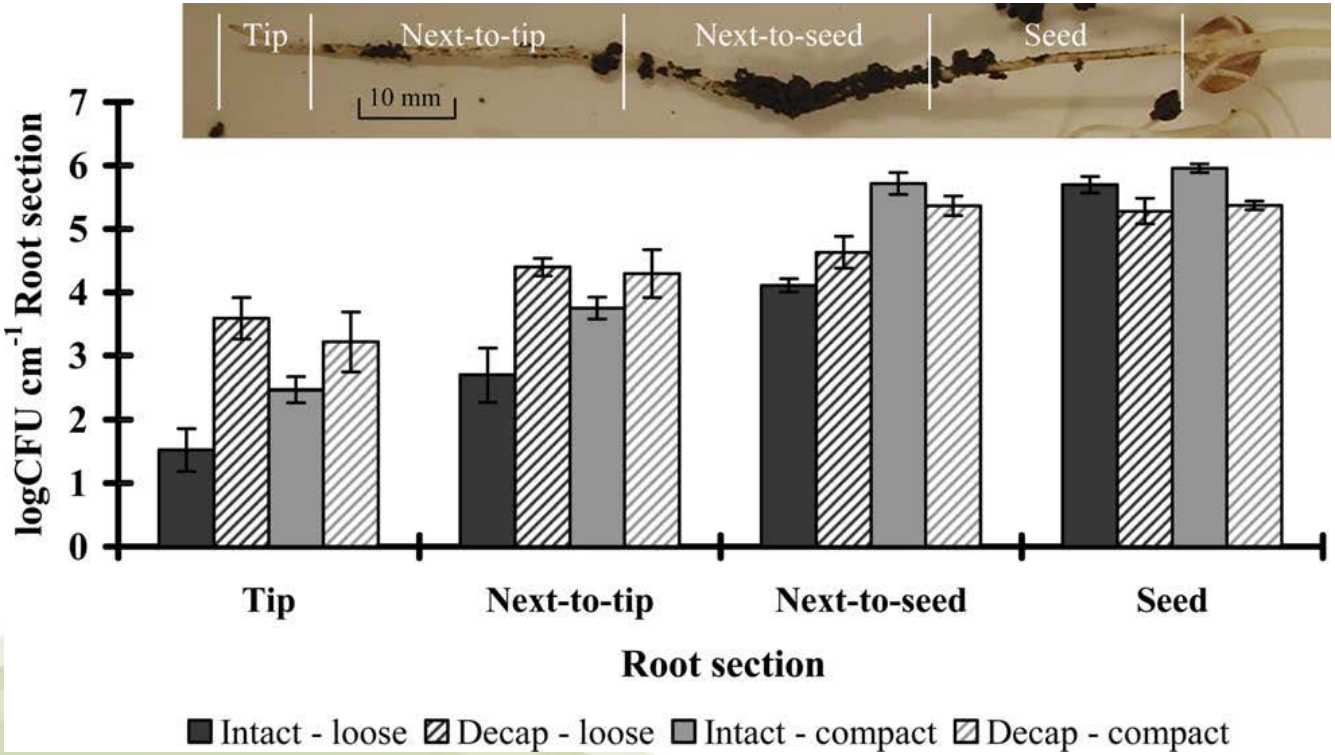
But literature is contradictory





Watt et al 2006a&b

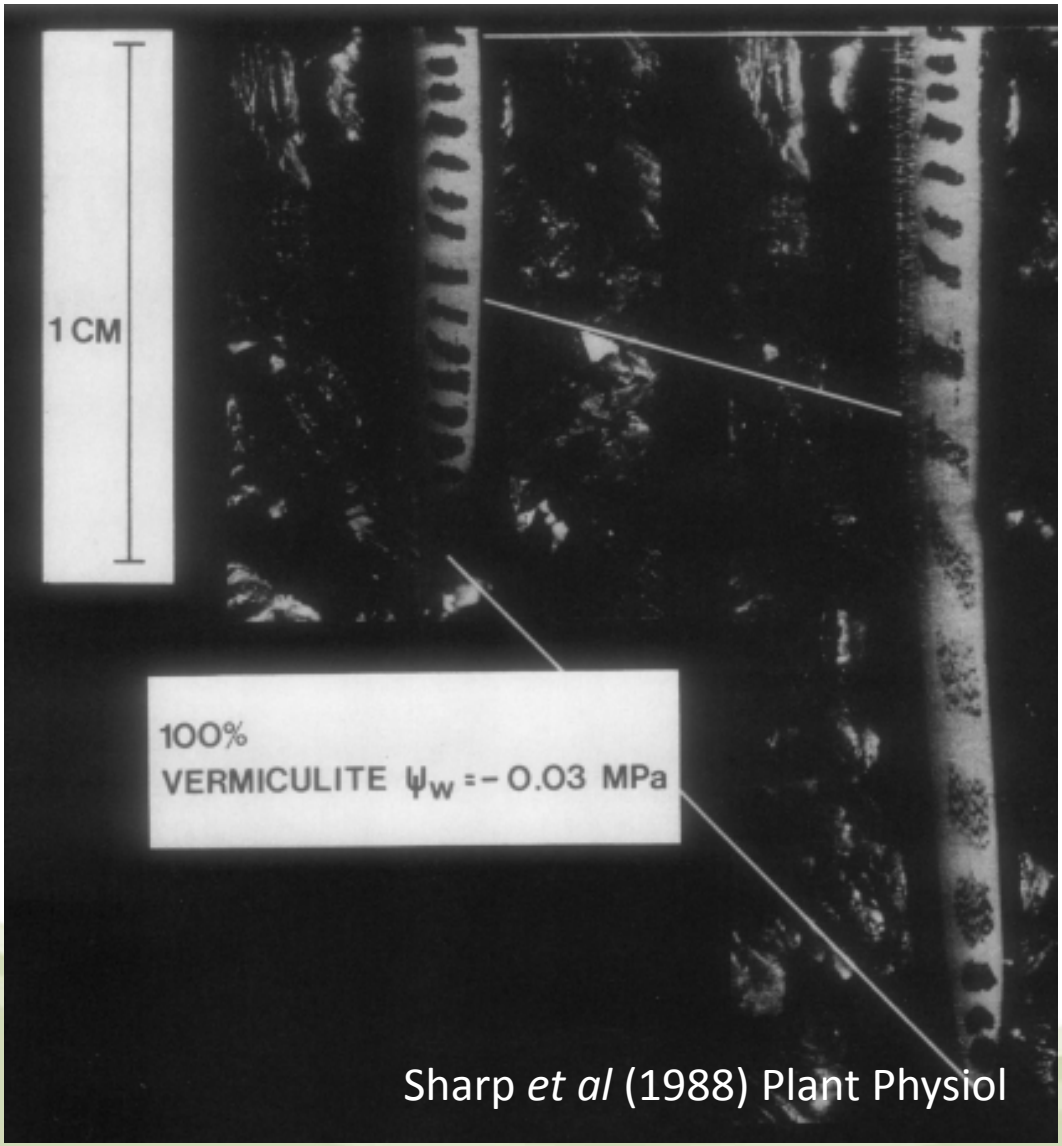
But literature is contradictory



Humphris et al 2005

Challenges of attaching at the tip

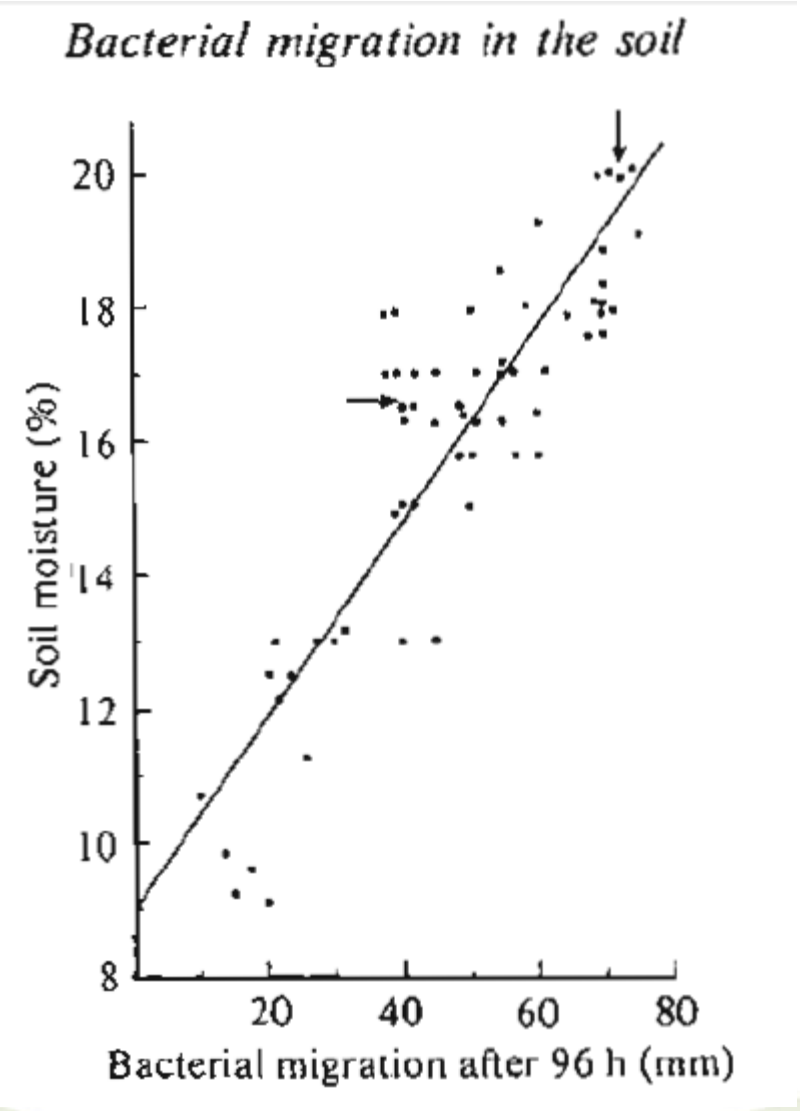
- Root cell movement
- Root cell elongation
- Efflux, border cells and sloughing



Sharp *et al* (1988) Plant Physiol

Bacterial mobility?

- Chemotaxis
- Root uptake / mass flow
- Soil properties
- Chemical gradients in the rhizosphere



Bashan 1986

A model to study establishment of bacteria on the root tip

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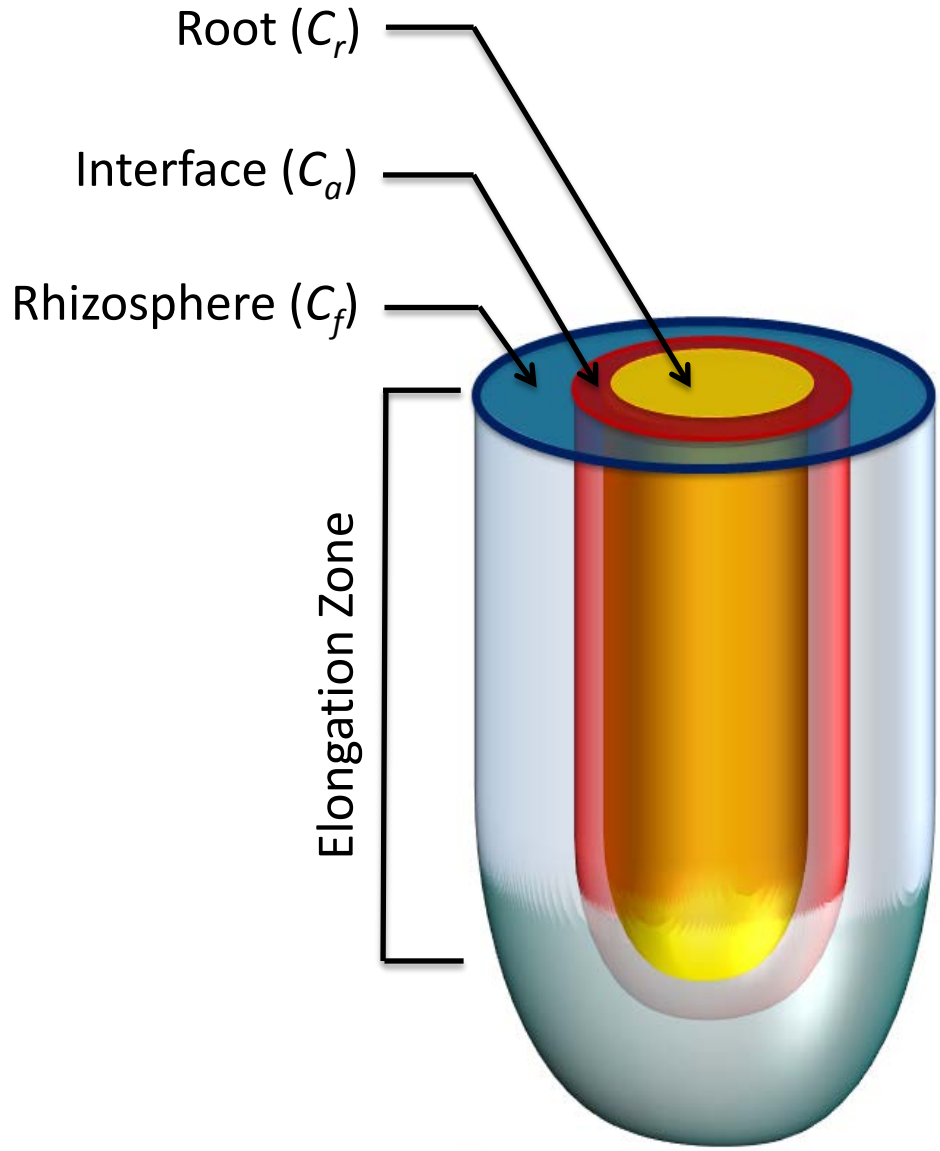
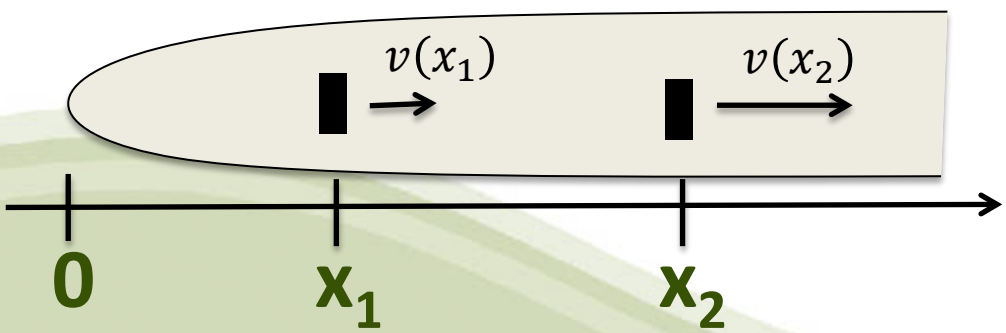
Rhizosphere geometry

- Rhizosphere soil
  - Cross section C_f
  - Free moving bacteria
- Root interface
  - Cross section C_a
  - Attached bacteria
- Root
  - Cross section C_r
  - Elongation zone



Moving reference frame

- Local coordinate **x** measures position along the root
- Centre of the frame at to the root tip (**x** = 0)
- no lateral cell movement, no explicit root cap in the model
- Cells flow away from the tip a velocity *v*

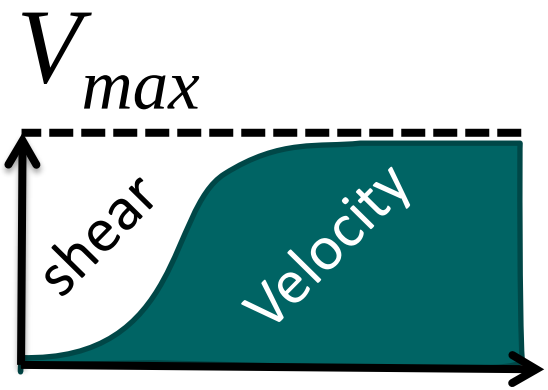


Root growth and function

- Root cell flow away from the tip (mm.d^{-1})

$$v(x) = V_{max}\{1 - \exp(-x^2/\mathrm{W})\}$$

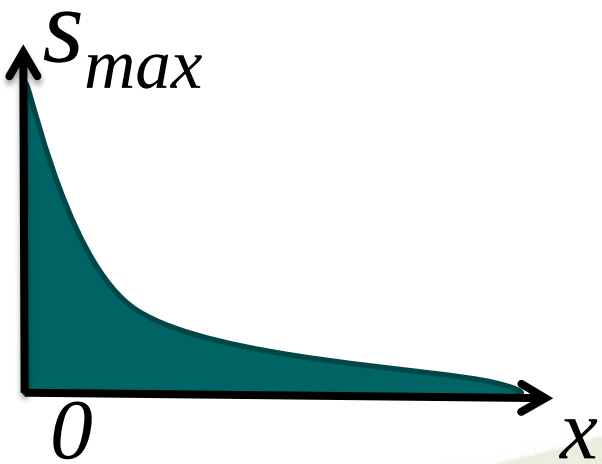
- Soil particles velocity is V_{max}



- Root / soil shear velocity $V_{max} - v$

- Root exudation (µg.cm^{-3})

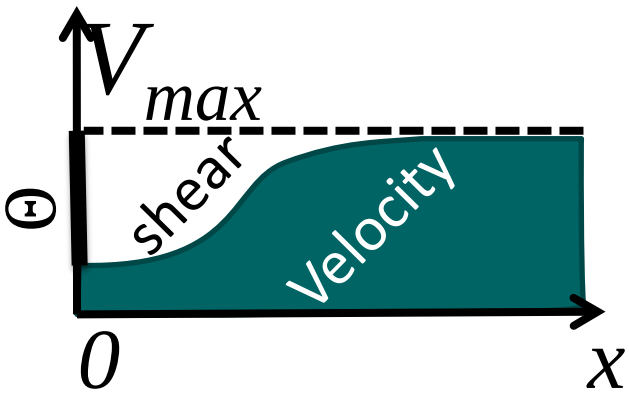
$$s(x) = S_{max} \exp(-x/\mathrm{L})\ /\mathrm{L}$$



Growth and transport of bacteria

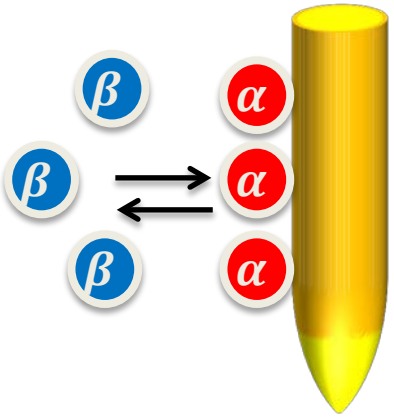
- Attached bacterial cell flow (mm.d^{-1})

$$v(x) = V_{max}\{1 - \Theta \exp(-x^2/W)\}$$



- Growth: Monod kinetics (d^{-1})

$$g(\alpha, \gamma) = G_{max}\frac{\gamma}{\gamma + K} - GY$$

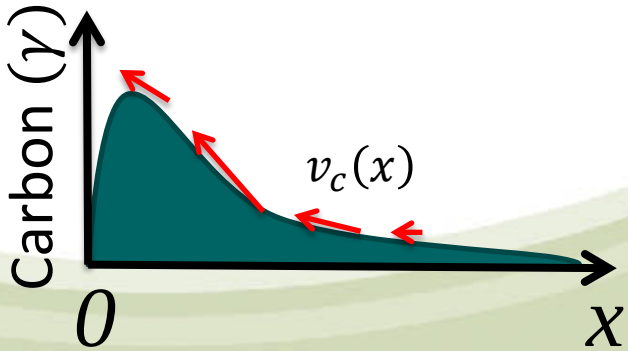


- Attachment: Languemuir Adsorption (µg.cm^{-3}.d^{-1})

$$a(\alpha, \beta) = AB\beta(N - \alpha) - B\alpha$$

- Chemotaxis - Keller and Seguel (mm.d^{-1})

$$v_c(x) = \chi\beta\partial_x\gamma$$



Putting it all together

- Conservation equation for $x \in [-L, L]$

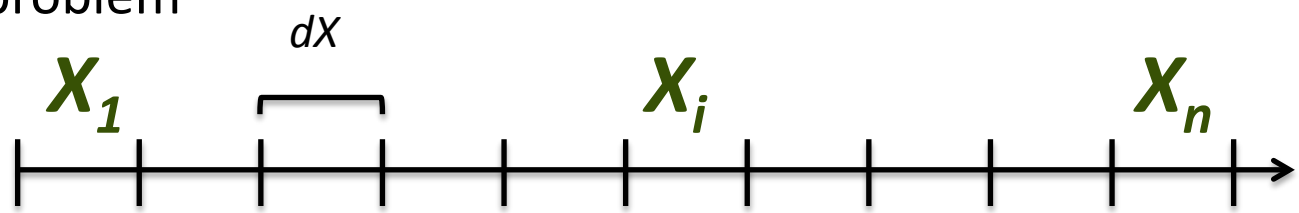
$$\begin{cases} \partial_t \alpha + \partial_x (v\alpha) = g\alpha + a \\ \partial_t \beta + \partial_x \{(V_{max} + \chi \partial_x \gamma)\beta - D\partial_x \beta\} = g\beta - C_a C_f^{-1} a \\ \partial_t \gamma + \partial_x (V_{max}\gamma - E\partial_x \gamma) = s - C_a g\alpha - C_f g\beta - P\gamma \end{cases}$$

- Imposed flux at boundaries $x = -L$

$$V_{max}\alpha = V_{max}\alpha_0$$
$$V_{max}\beta = V_{max}\beta_0$$
$$V_{max}\gamma = V_{max}0$$

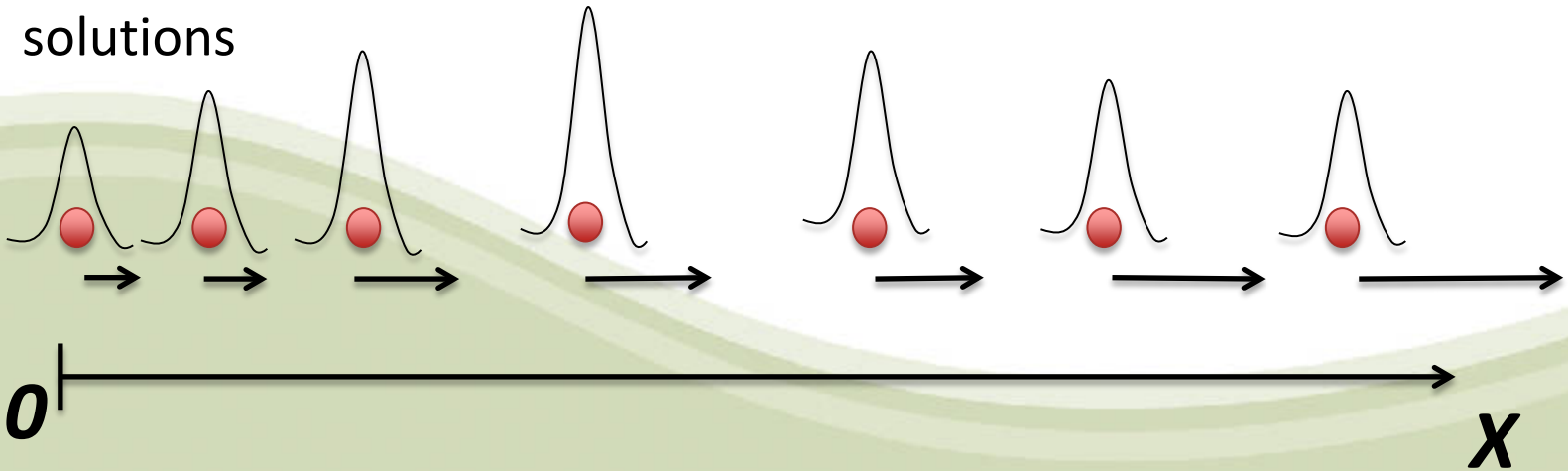
Solving the model

- Steady state solution solved as initial value problem



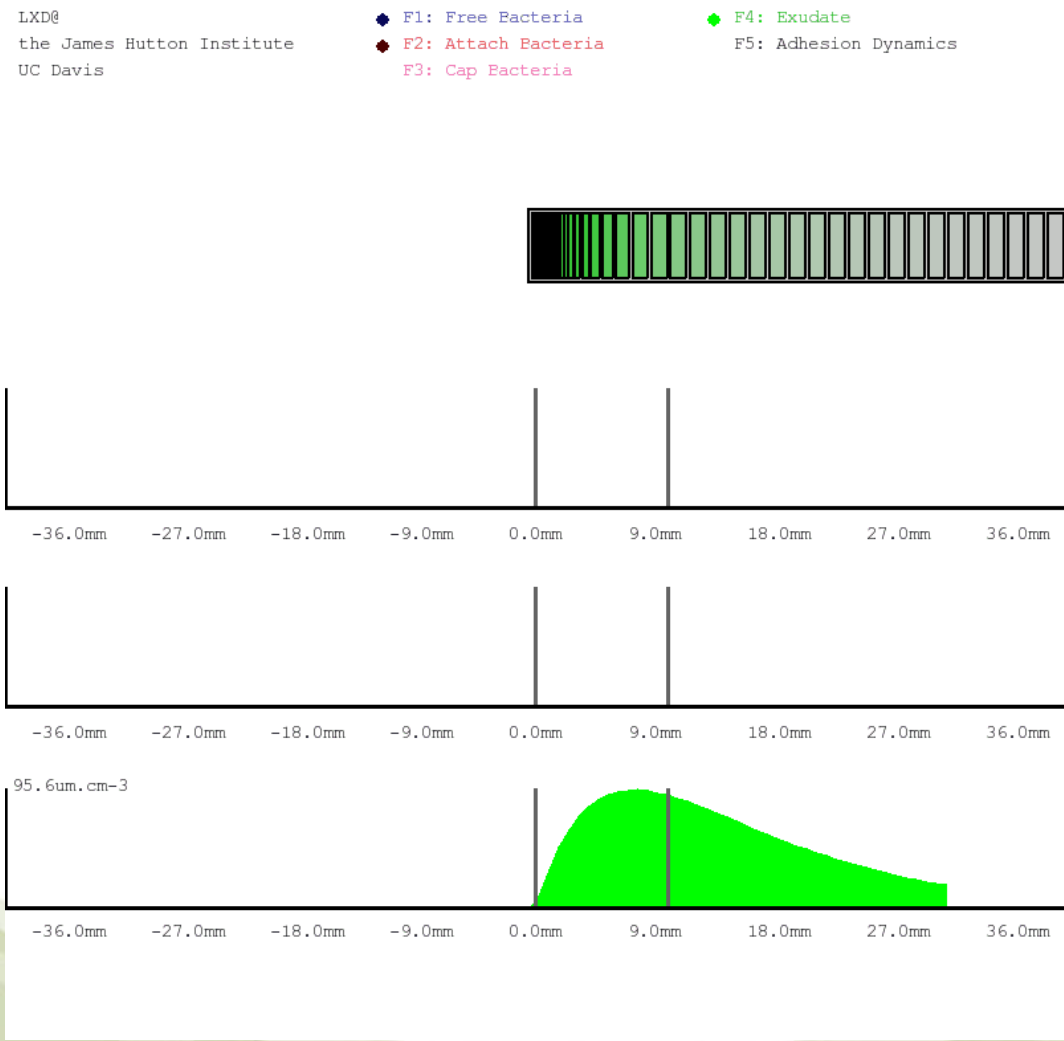
$$X_{i+1} = f(X_i)*dX$$

- Smoothed-particle hydrodynamics for transient solutions

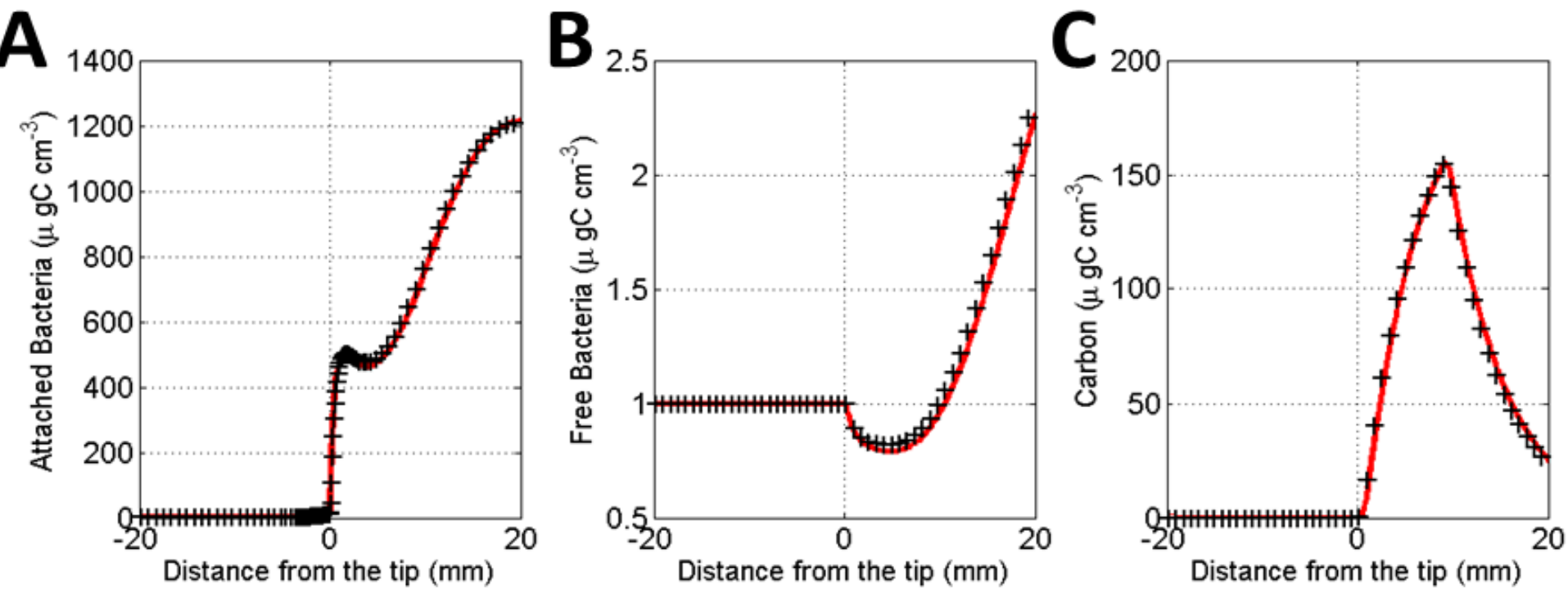


Smoothed Particle Hydrodynamics

- Simple
- Facilitate Biological interpretation
- Fast



Testing the model

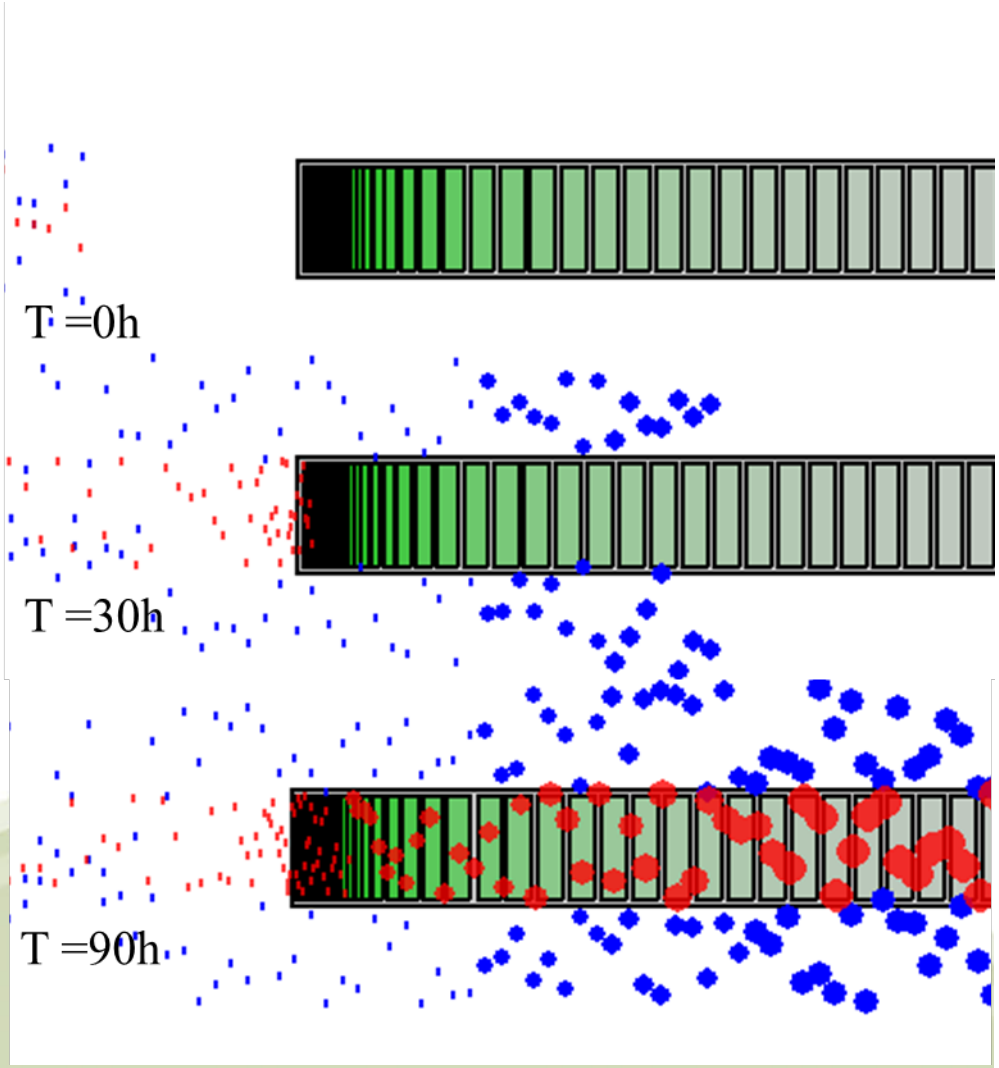


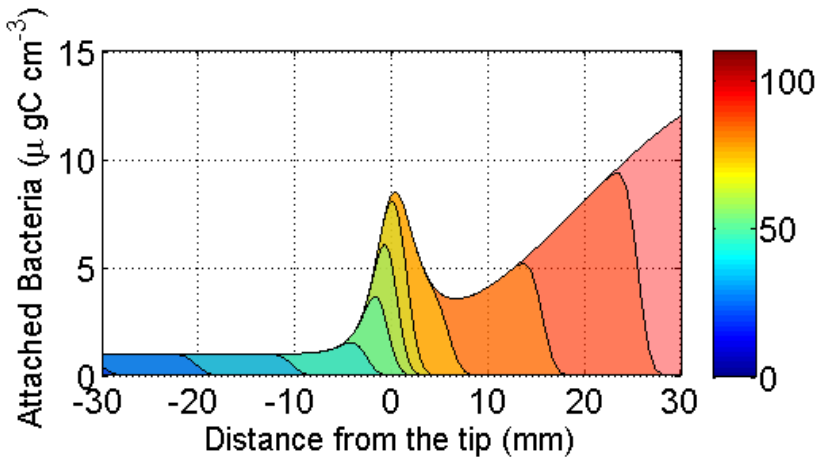
There’s an app for that!

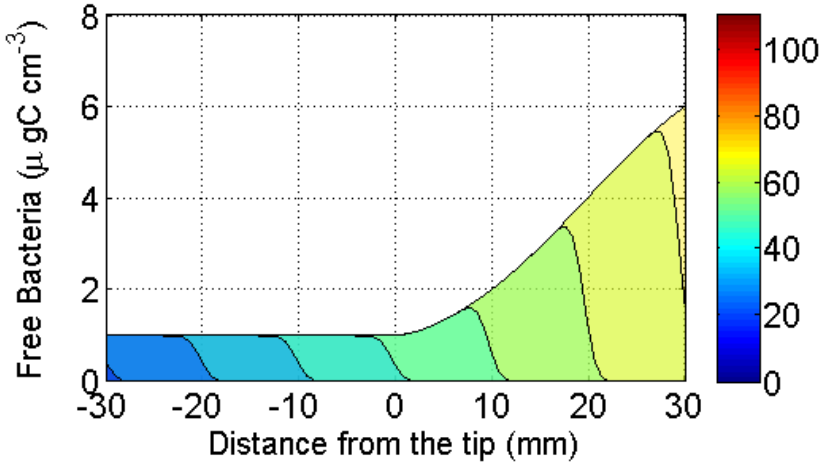
Rhizobact

What’s the model is telling us

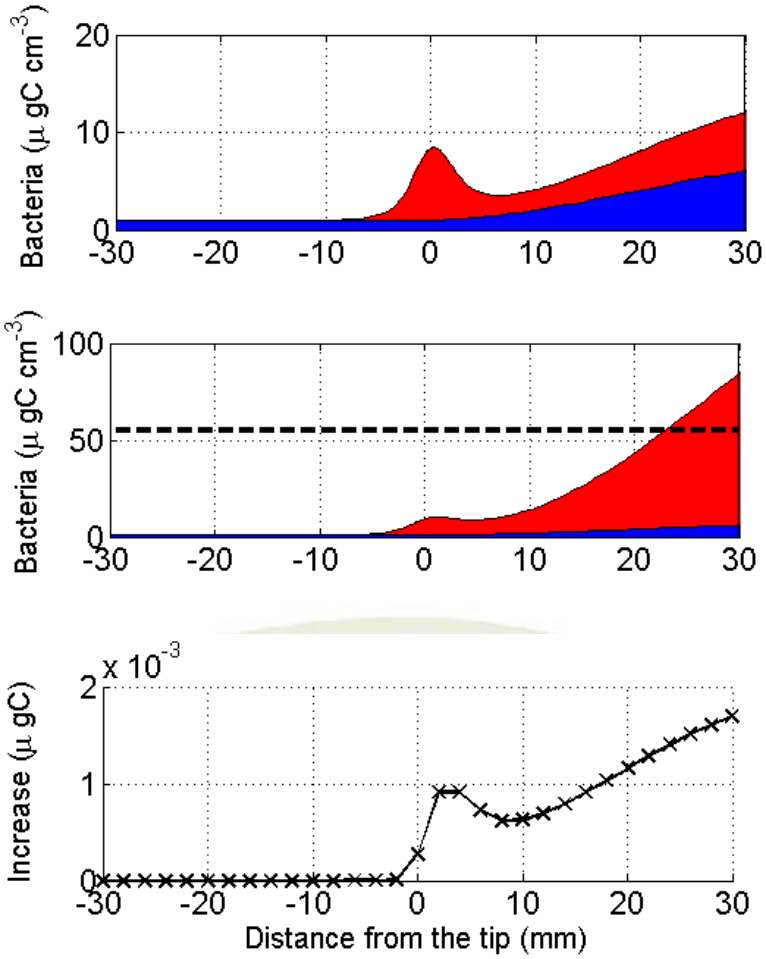
Attachment increases availability of nutrients at low energetic cost

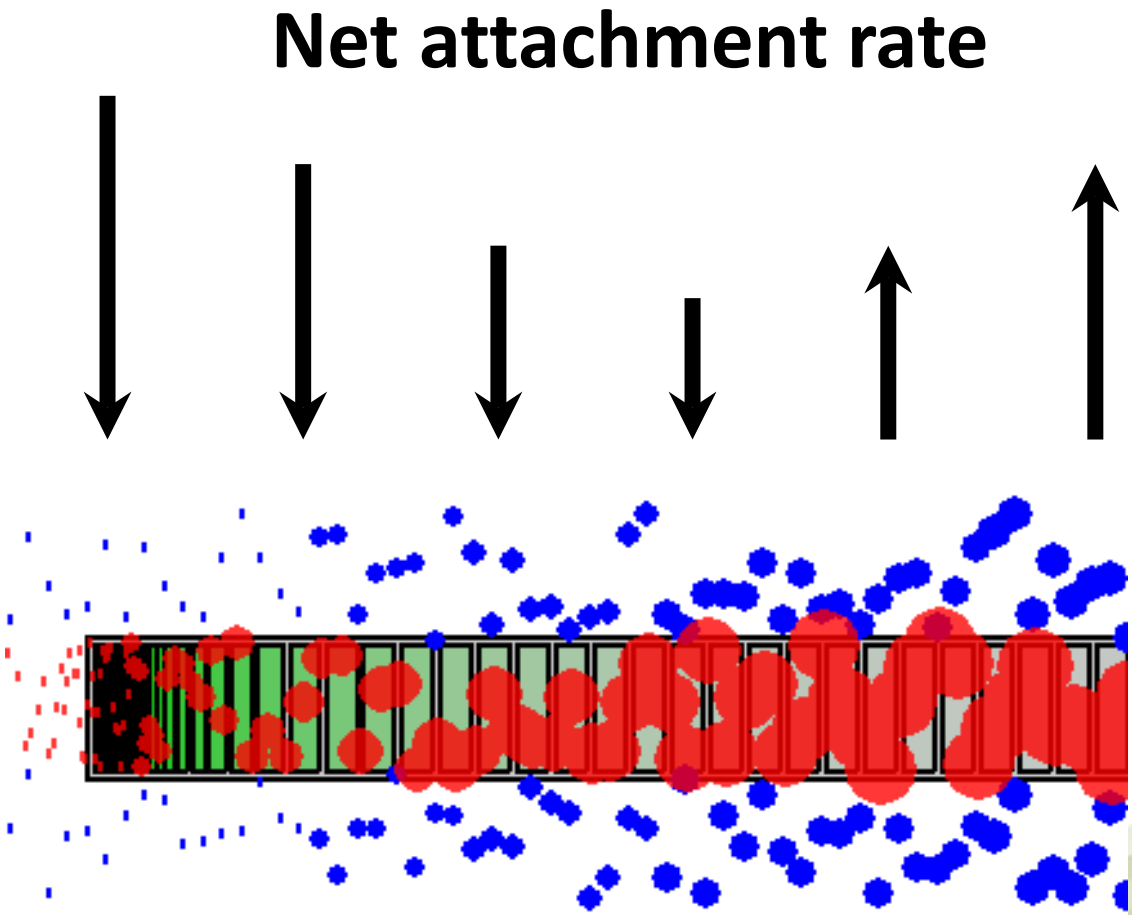






Dynamic attachment /detachment is a reversible process

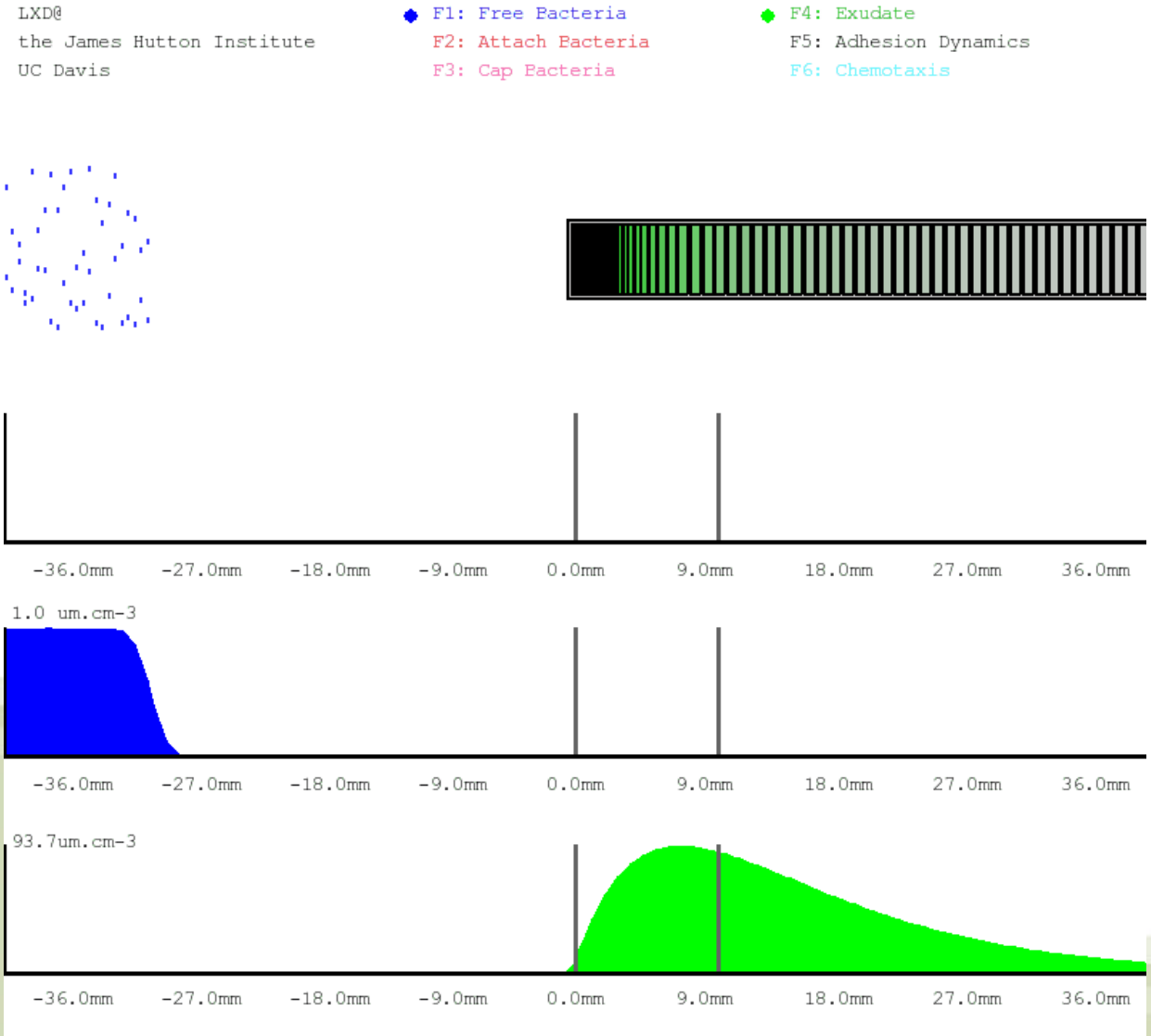


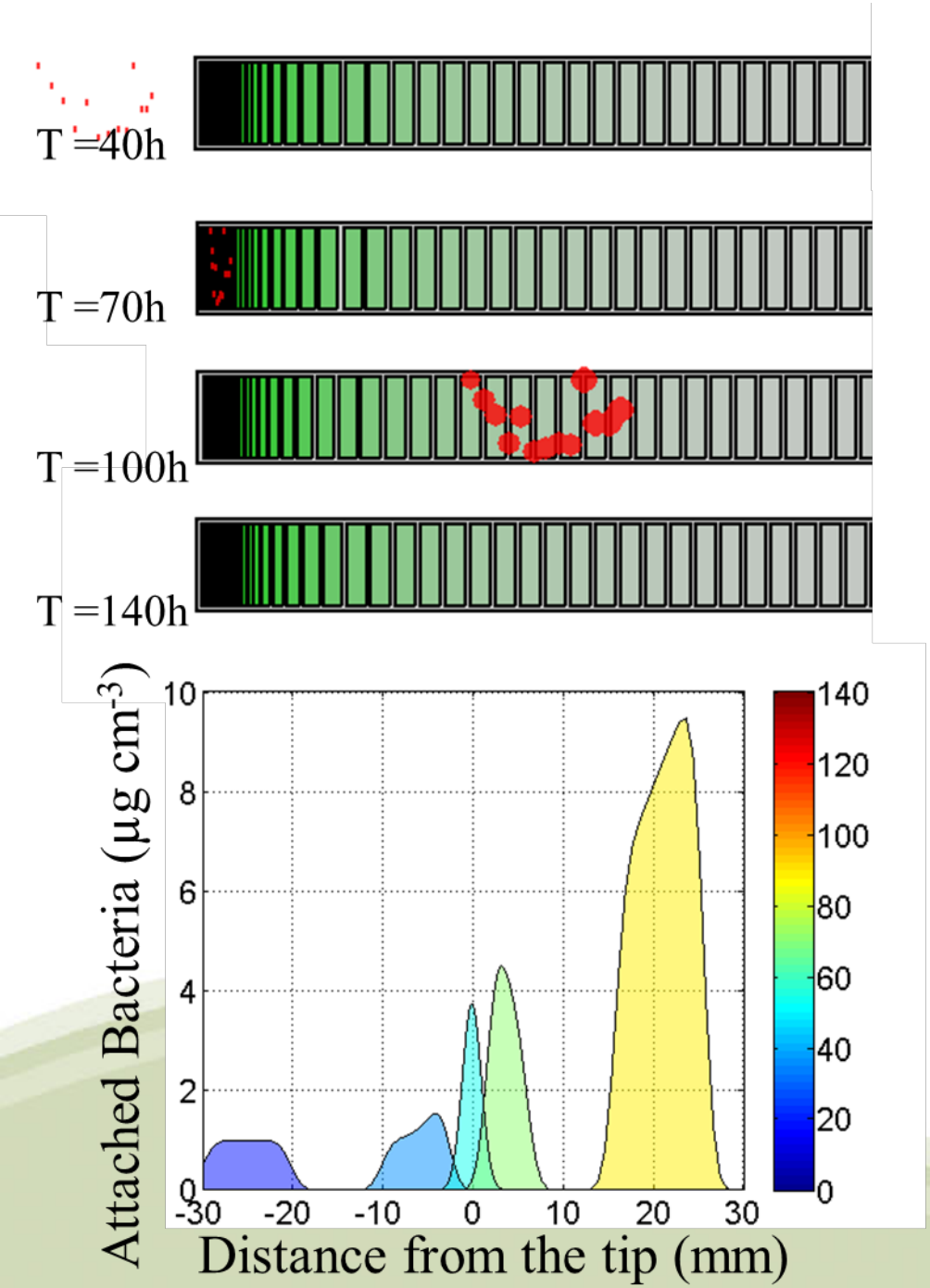


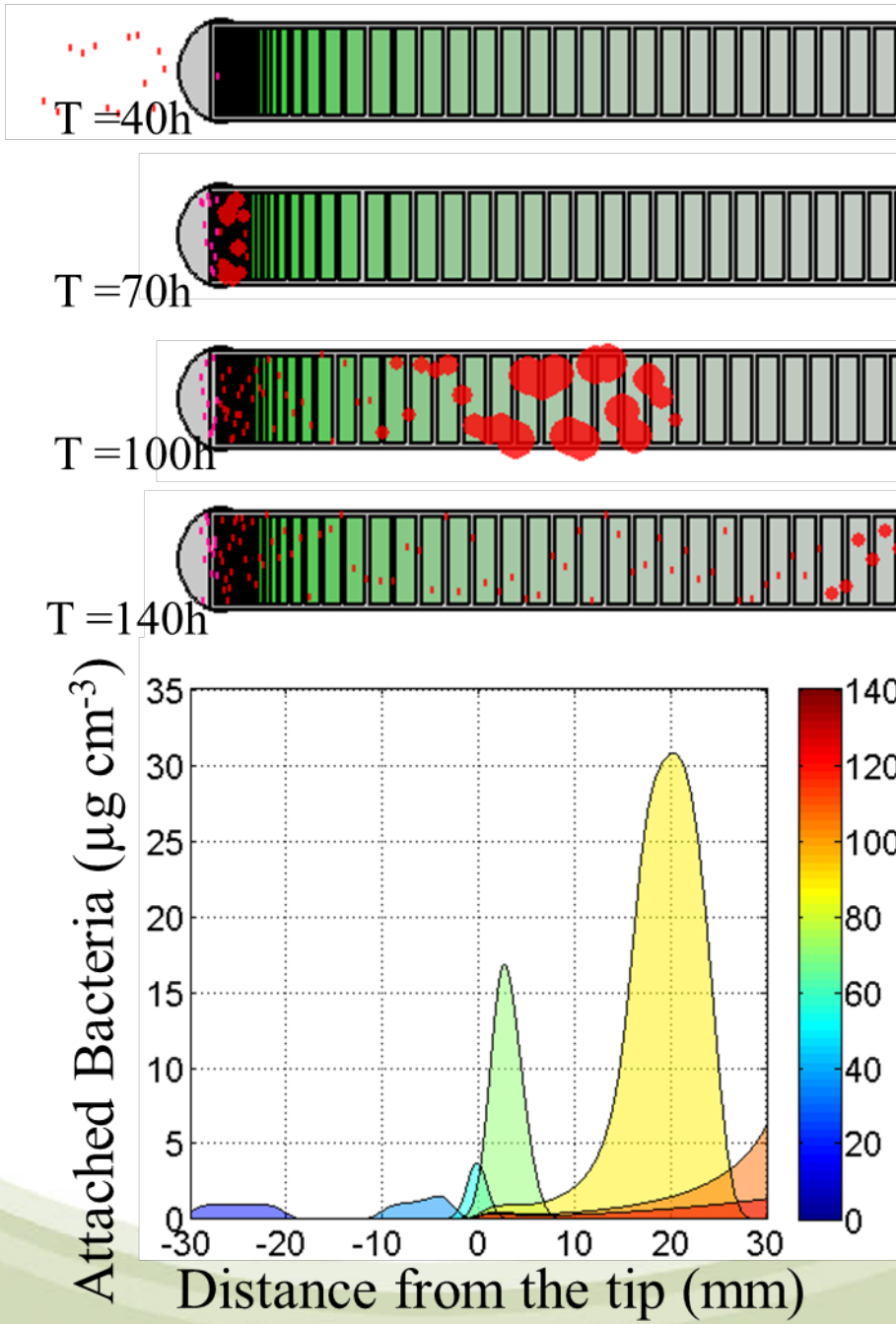
Chemotaxis unlikely to explain colonisation of the tip

- Unsaturated soil conditions limits bacterial movements
- Peak of exudates in the elongation zone due to growth
- No experimental quantification of longitudinal movement
- Radial movement vs longitudinal movement
- Energetic cost
- Predicted patterns of bacteria distribution unrealistic

Chemotaxis unlikely to explain colonisation of the tip




T =40h
T =70h
T =100h
T =140h
Attached Bacteria (µg cm-3)
Distance from the tip (mm)


T =40h
T =70h
T =100h
T =140h
Attached Bacteria (µg cm-3)
Distance from the tip (mm)

A multitude of factors controls colonisation of root surfaces

+++ Elongation rate

++ Attachment rate and ability to exploit exudate

++ Root exudation

+ Bacterial motility

Summarizing

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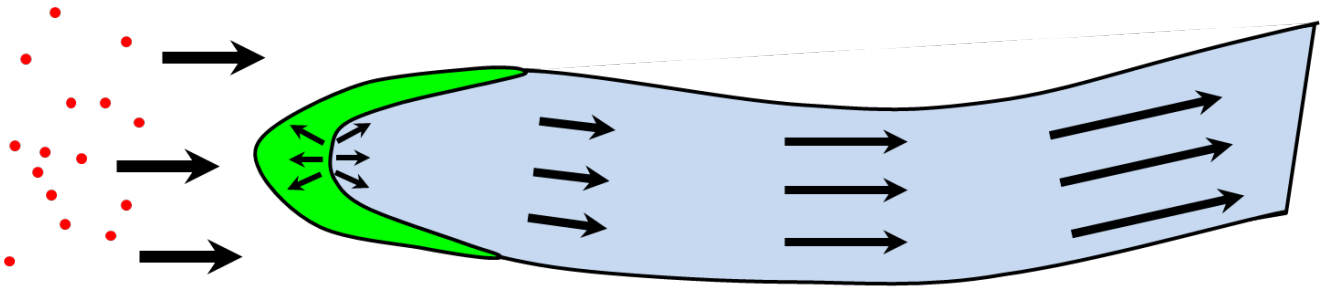
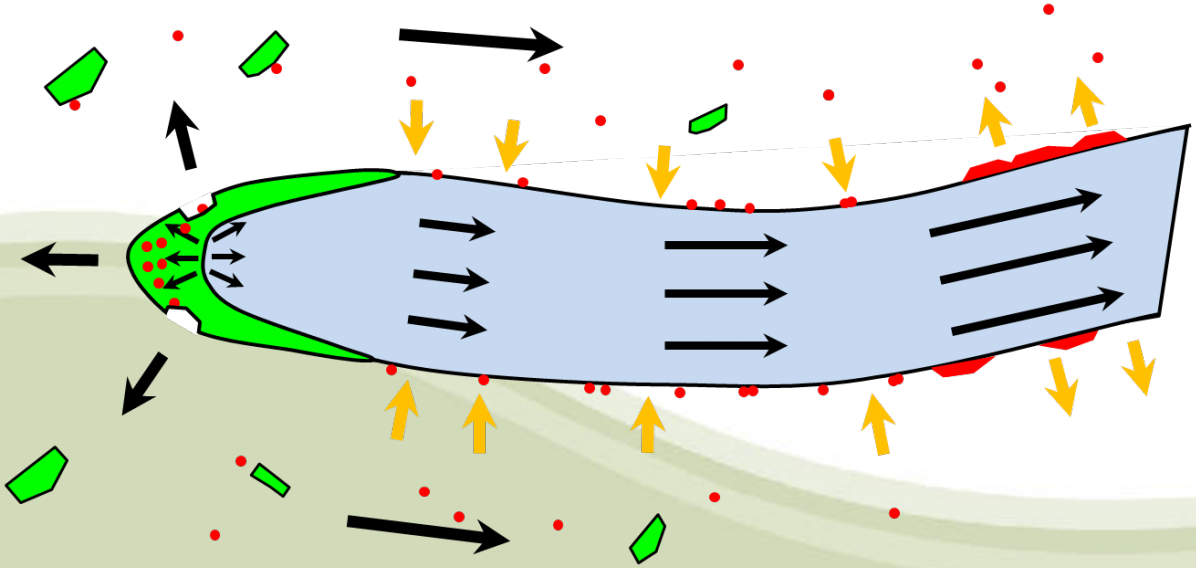
General Model for Bacterial colonisation of the root tip





Potential of this new approach

- The model is simple
- New insights into root bacteria interactions
- Potential for generalisation / improvements

  multi-species, attachment, soil properties …
- Root cap not completely resolved

Thanks!

Colleagues from UC Davis

Daniel Geisseler, Kate Scow, Alison Berry

Wendy Silk, Matt Dumlao

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