LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY
LIST

Water and vegetation in a changing environment: Optimal adaptation, feedbacks and key trade-offs

Stanislaus J. Schymanski

Gitanjali Thakur

Remko C. Nijzink

Louis Krieger

Emmanuella Osuebi-Iyke

Samuele Ceolin

Catchment and Ecohydrology Group
(CAT < ENVISION < ERIN)
Luxembourg Institute of Science and Technology

Peak Charles NP, Western Australia

WAVE – Water and Vegetation in a changing environment
Capturing change and feedbacks of vegetation, atmosphere and hydrology, with an open science approach
https://zenodo.org/communities/wave Contact: stanislaus.schymanski@list.lu

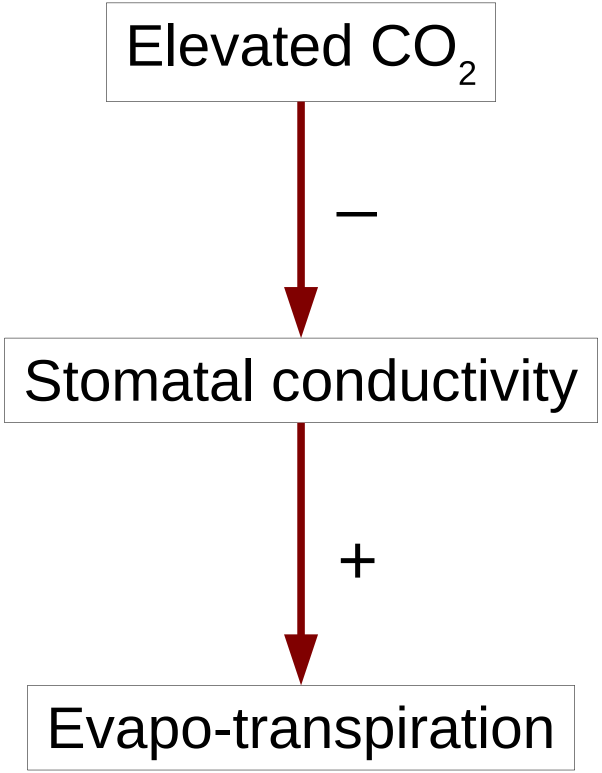
Sharing is encouraged

Fonds National de la Recherche Luxembourg

Supported by FNR ATTRACT (A16/SR/11254288)

ADAPTATION TO ELEVATED CO2

Gedney et al. (2006):
Nature 439(7078)



CO_2-Adapt.
Carbon profit
Optimality
Trade-offs

ADAPTATION TO ELEVATED CO2

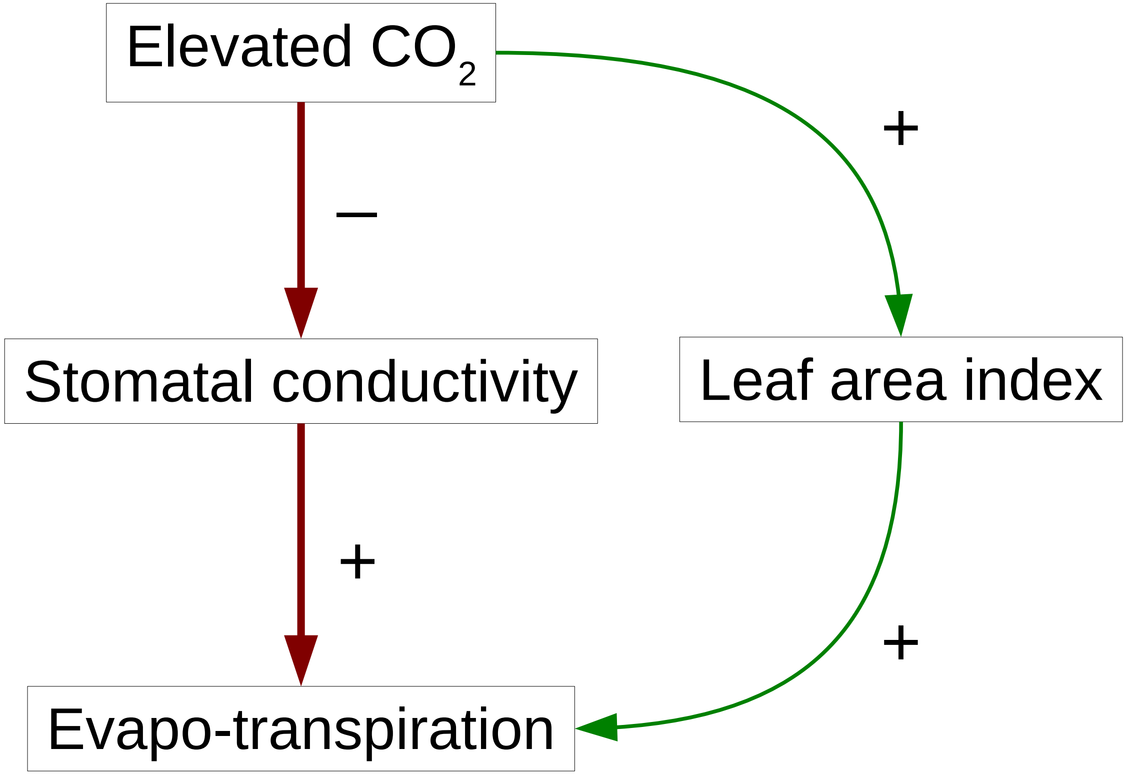
CO_2-Adapt.
Carbon profit
Optimality
Trade-offs

Gedney et al. (2006): Nature 439(7078)

Piao et al. (2007): PNAS 104(39)

Short term

Medium term



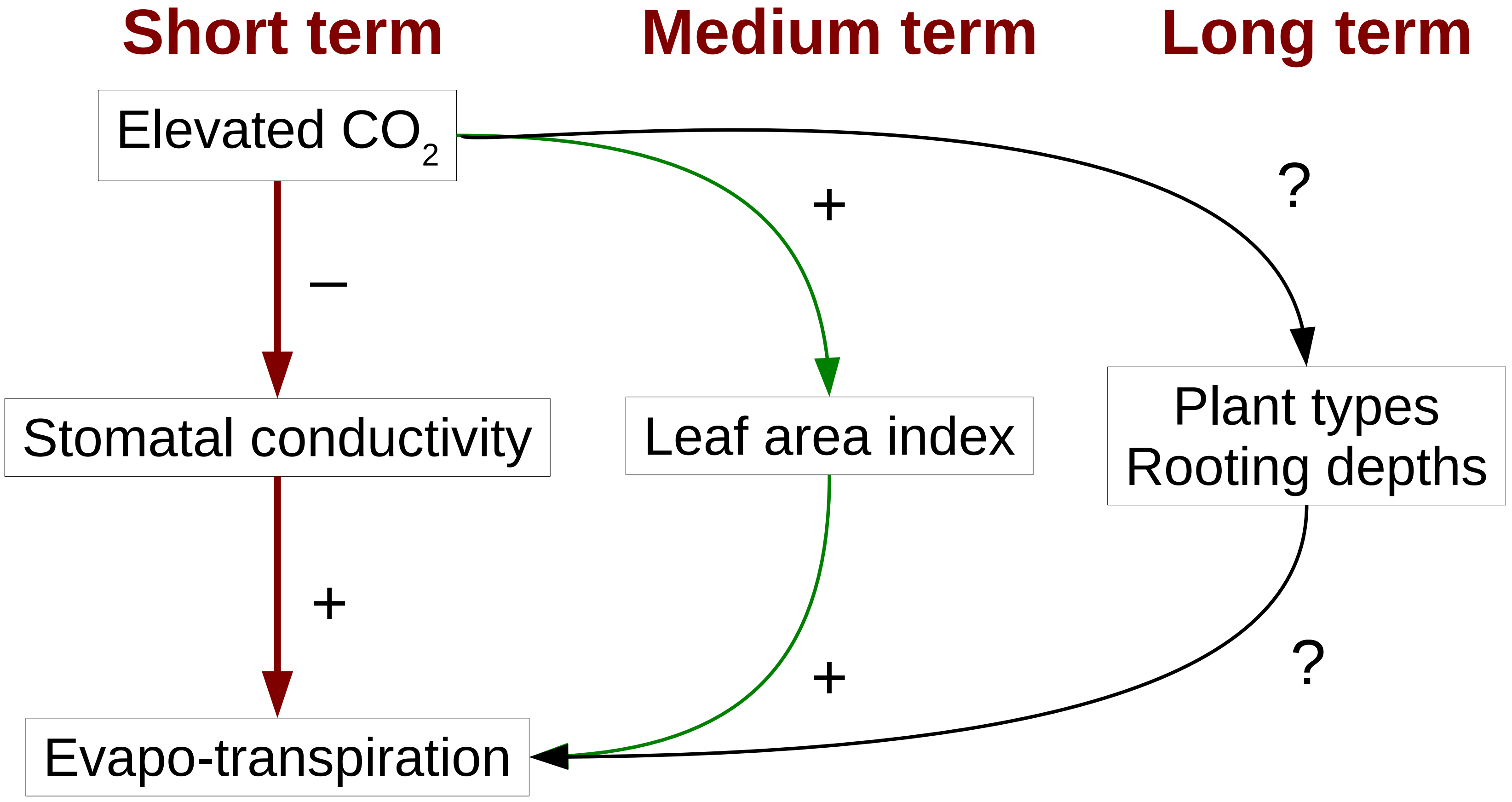
ADAPTATION TO ELEVATED CO_2

LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST

Gedney et al. (2006): Nature 439(7078)

Piao et al. (2007): PNAS 104(39)

Schymanski et al. (2015): AoB Plants 7



CO_2-Adapt.

Carbon profit

Optimality

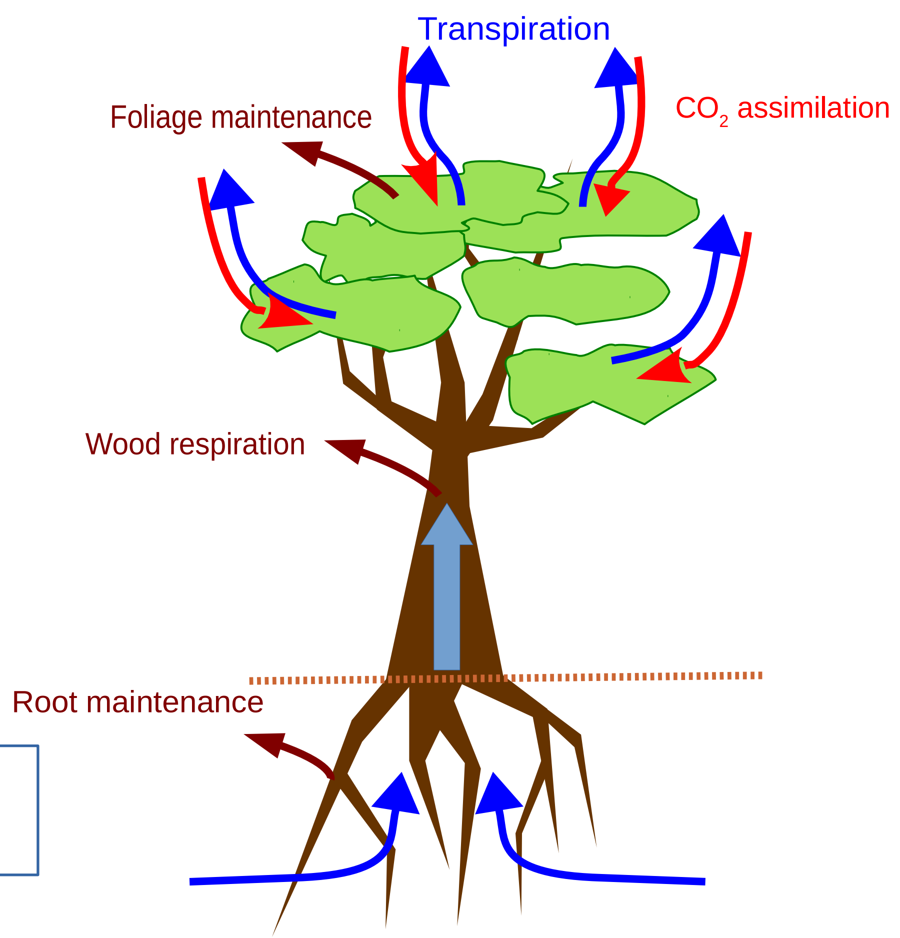
Trade-offs

BG 3.4
EGU22-8841
Schymanski et al.

GENERAL PRINCIPLES BEHIND VEGETATION RESPONSES?

- Carbohydrates as energy currency
- Leaf gas exchange determines gross income
- Trade-offs between carbon gain and loss guide economics
- Selective pressure for best use of resources to **maximise the Net Carbon Profit**

→ **Vegetation Optimality Model (VOM): Schymanski et al. 2009, WRR 45**



ADAPTATION TO ELEVATED CO_2: VEGETATION OPTIMALITY MODEL (VOM)

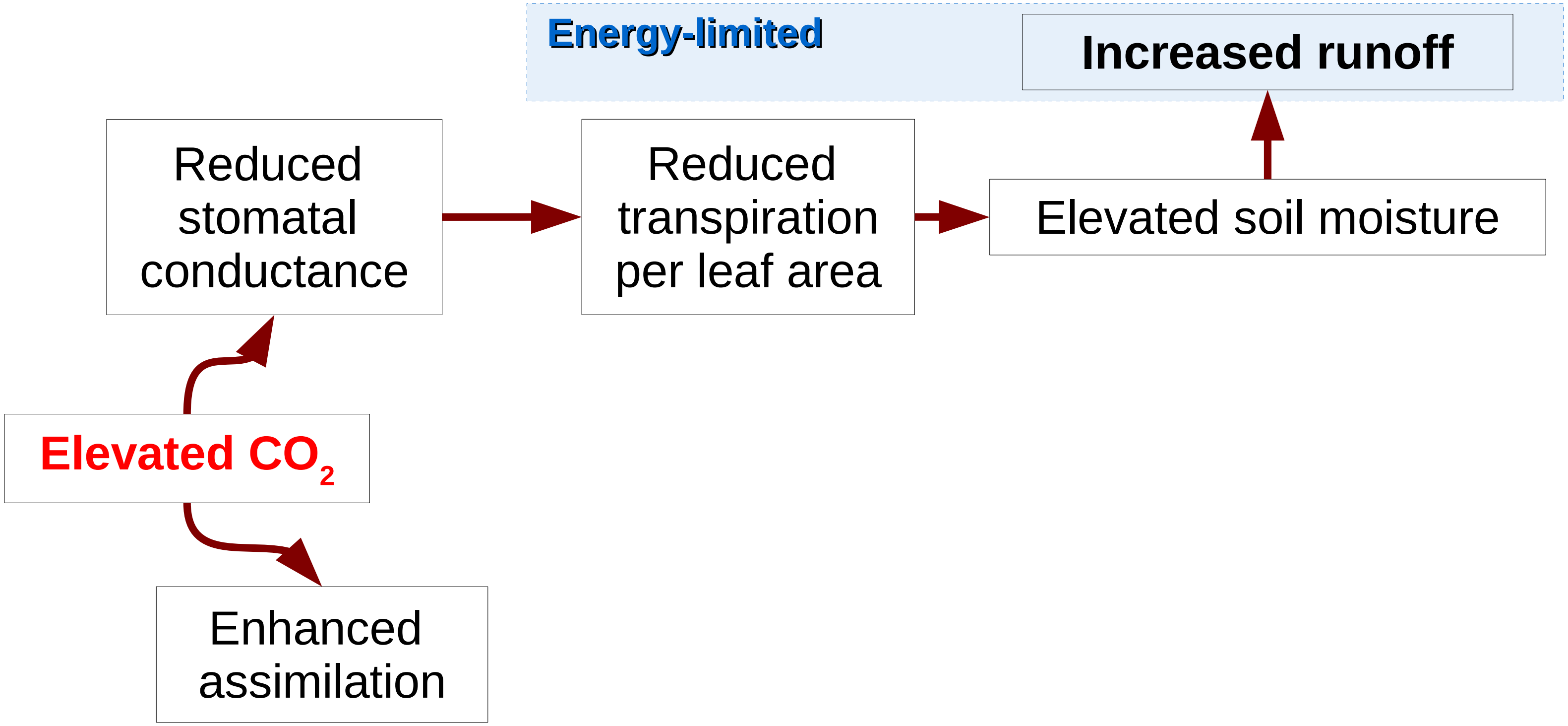
LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST

CO_2-Adapt.

Carbon profit

Optimality

Trade-offs

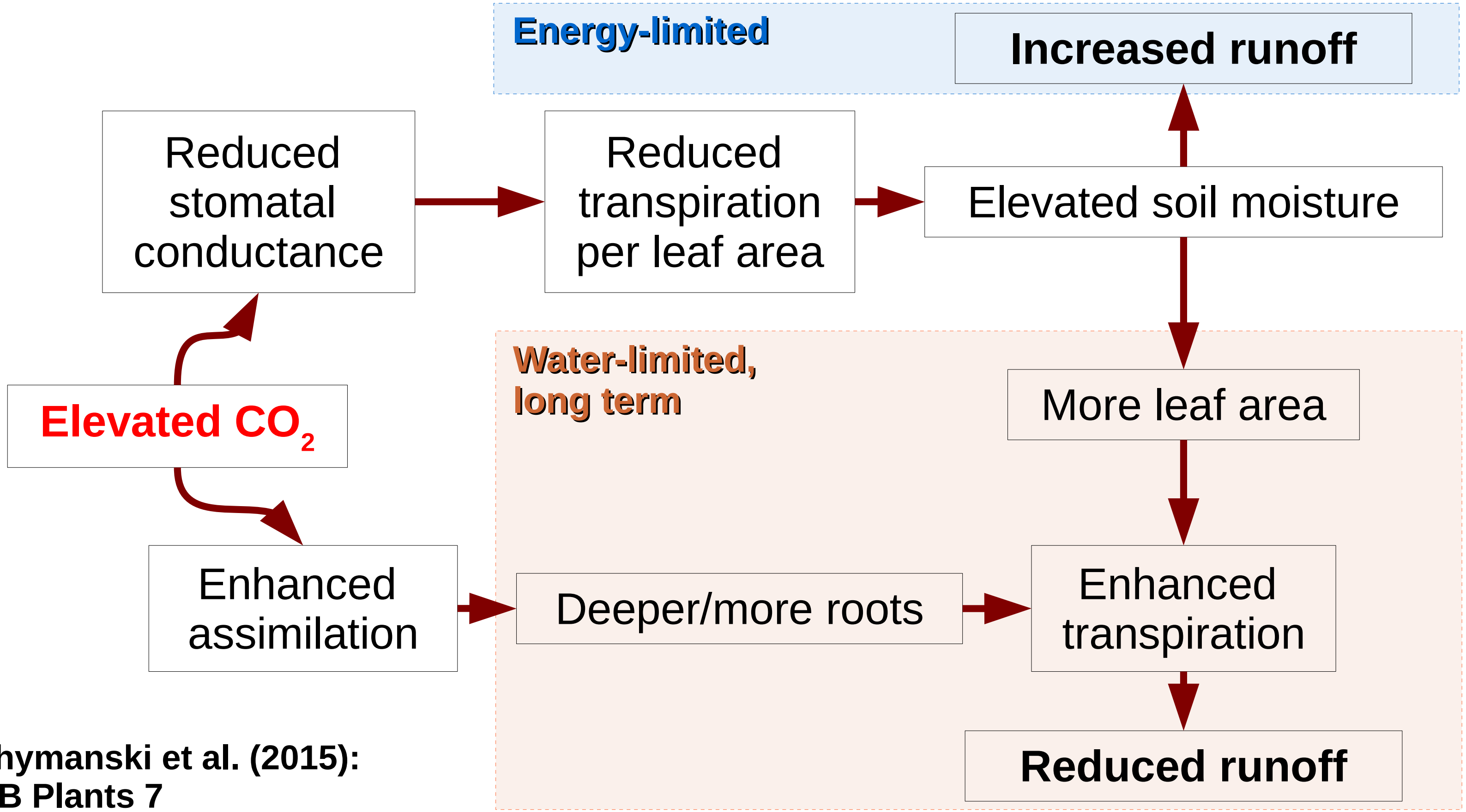


BG 3.4
EGU22-8841
Schymanski et al.

Schymanski et al. (2015): AoB Plants 7

ADAPTATION TO ELEVATED CO_2: VEGETATION OPTIMALITY MODEL (VOM)

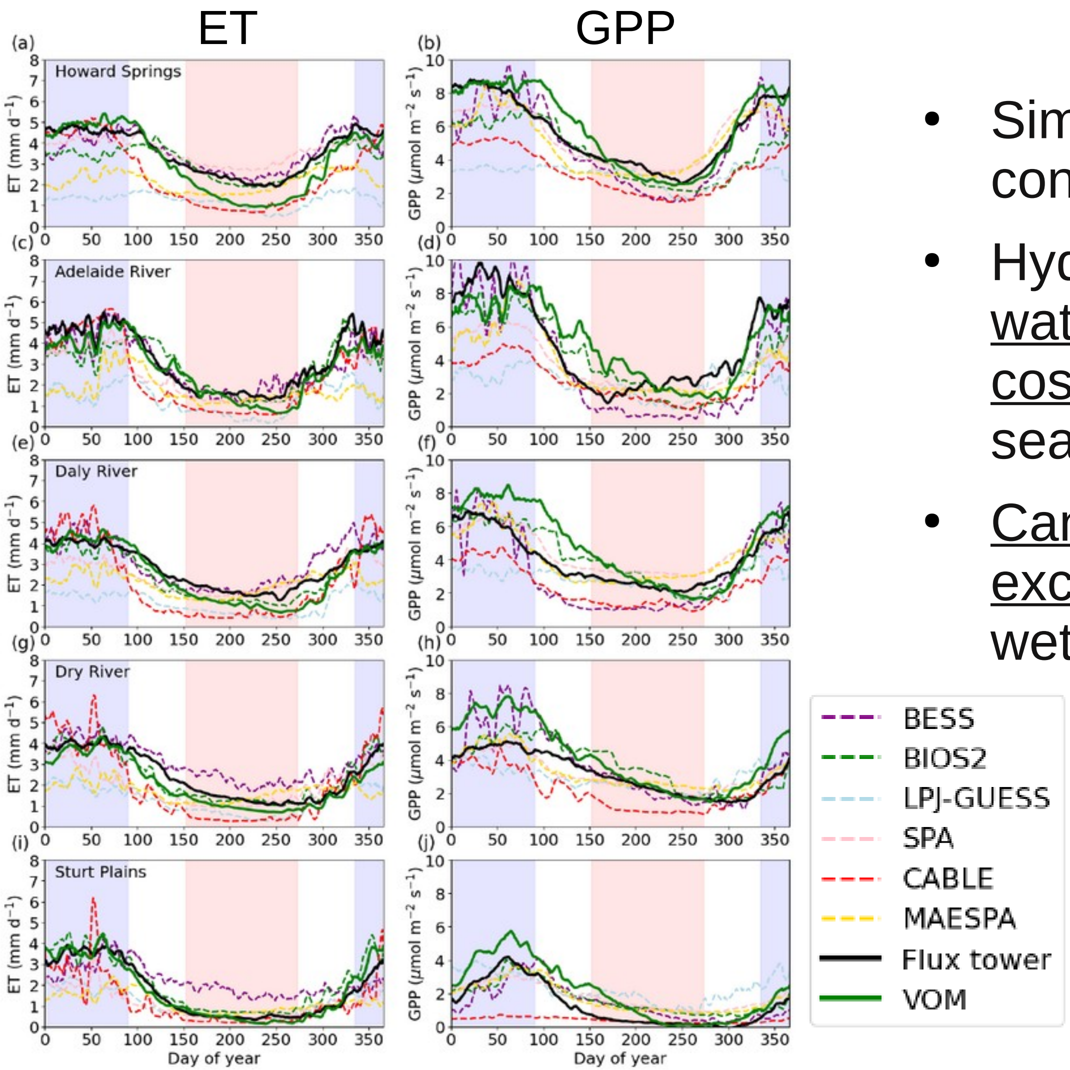
LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST



Schymanski et al. (2015): AoB Plants 7

VEGETATION OPTIMALTIY PREDICTS ET & GPP

LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY
LIST



- Similar or better results than conventional models
- Hydrology feedback and <u>water uptake and transport costs</u> important for dry season fluxes
- <u>Canopy light absorption & gas exchange limits</u> important for wet season fluxes

CO_2-Adapt.

Carbon profit

Optimality

Trade-offs

Nijzink, R. C. et al. (2022): HESS 26(2)
https://doi.org/10.5194/hess-26-525-2022

BG 3.4
EGU22-8841
Schymanski et al.

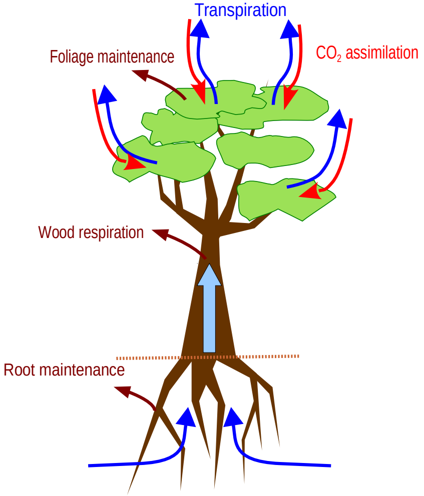
PROMISES AND CHALLENGES OF OPTIMALITY-BASED MODELLING

LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST

CO_2-Adapt.
Carbon profit
Optimality
Trade-offs

- General principles → performance in the past should indicate <u>performance in the future</u>
- Need to <u>quantify</u> physical and biological <u>limits</u>
- Need to <u>quantify trade-offs</u> between costs and benefits of carbon investments

"Change in Hydrology and Society"
(Montanari et al., 2013, HSJ 58(6))



NEED TO QUANTIFY PHYSICAL LIMITS AND TRADE-OFFS RELATED TO C INVESTMENT

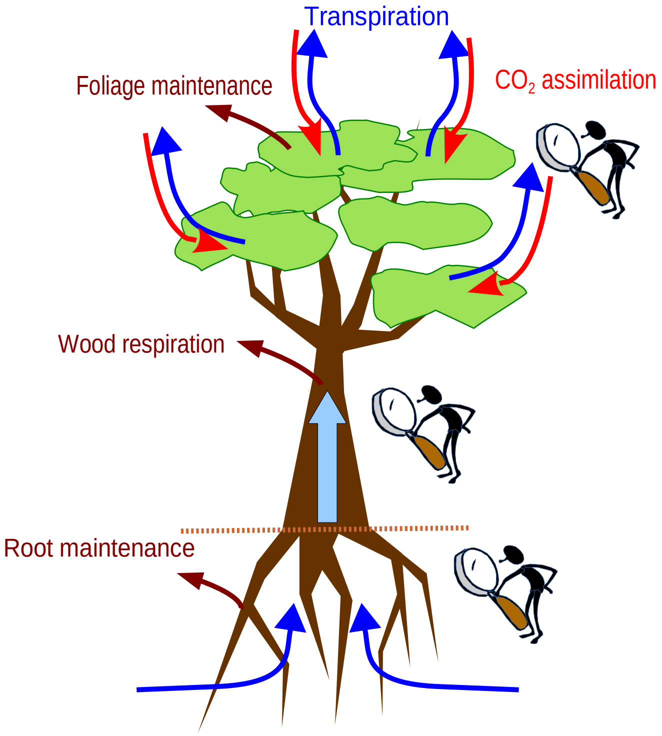
LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST

CO_2-Adapt.

Carbon profit

Optimality

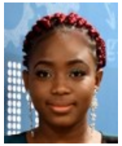
Trade-offs



- Nijzink et al.: LAI and light interception: EGU22-2886.html
- Thakur et al.: Leaf vs. canopy resistances: EGU22-4268.html
- Osuebi et al.: Shoot vs. root C flux experiments: EGU22-5798.html
- Krieger et al.: Plant hydraulic conductivity experiments: EGU22-5357.html
- Ceolin et al.: Root system dynamics experiments: EGU22-5306.html


R. Nijzink


G. Thakur


E. Osuebi-Iyke


L. Krieger


S. Ceolin

BG 3.4
EGU22-8841
Schymanski et al.

APPENDIX...

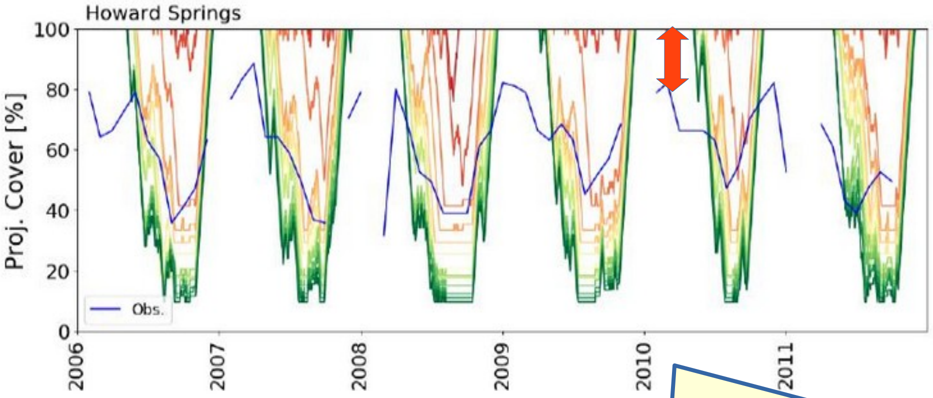
TRADE-OFFS RELATED TO LAI AND CANOPY LIGHT CAPTURING

CO$_2$-Adapt.

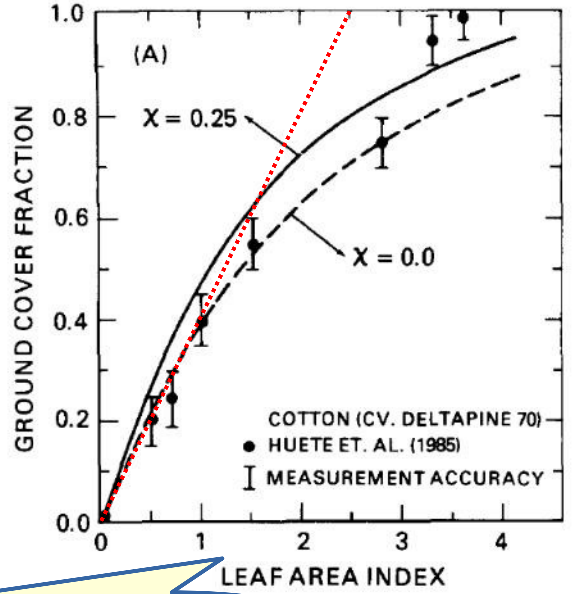
Carbon profit

Optimality

Trade-offs



Assumption in the VOM: LAI of 2.5 results in full cover (100% light interception)



Choudhury (1987): RSE 22

Reality: cover fraction is non-linear function of LAI

Why do plants waste so much leaf area instead of growing one big leaf?

Nijzink et al.: LAI and light interception: EGU22-2886.html

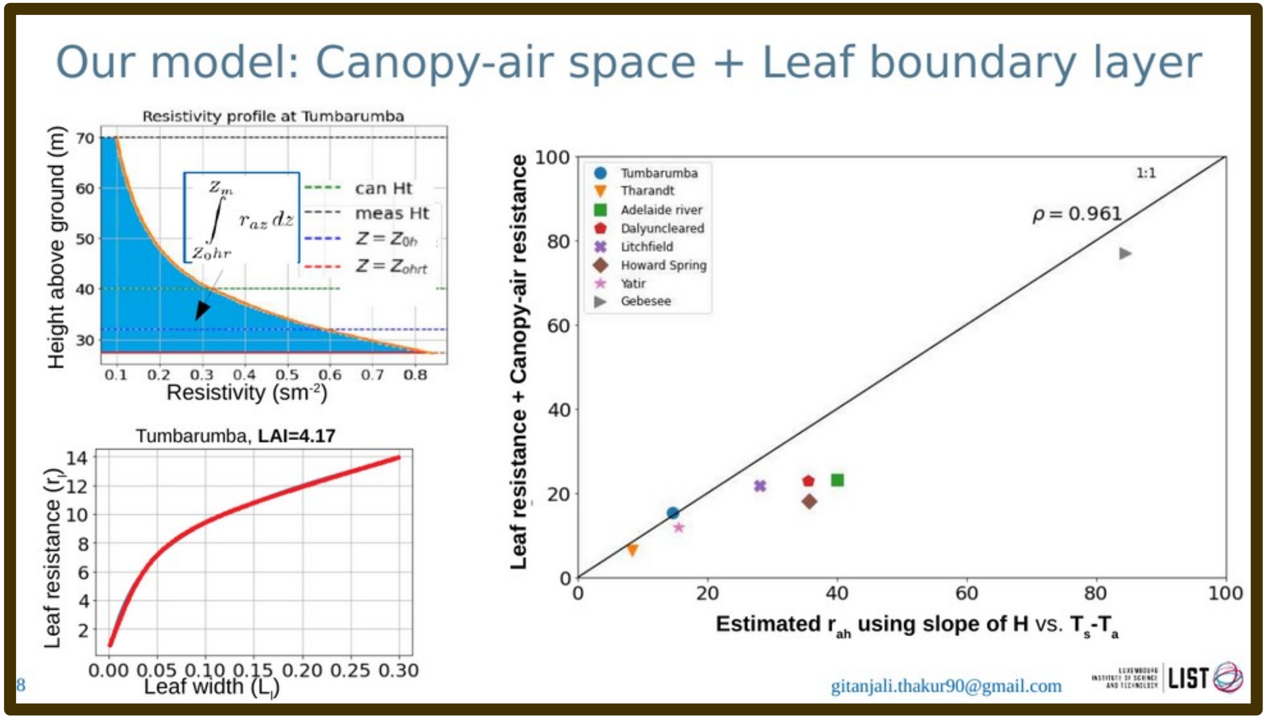
PHYSICAL LIMITS OF CANOPY GAS EXCHANGE

CO_2-Adapt.

Carbon profit

Optimality

Trade-offs



Thakur et al.: Leaf vs. canopy resistances: EGU22-4268.html

BG 3.4
EGU22-8841
Schymanski et al.

TRADE-OFFS RELATED TO WATER TRANSPORT AND STORAGE

CO_2-Adapt.
Carbon profit
Optimality
Trade-offs

Higher wood density (smaller vessels)

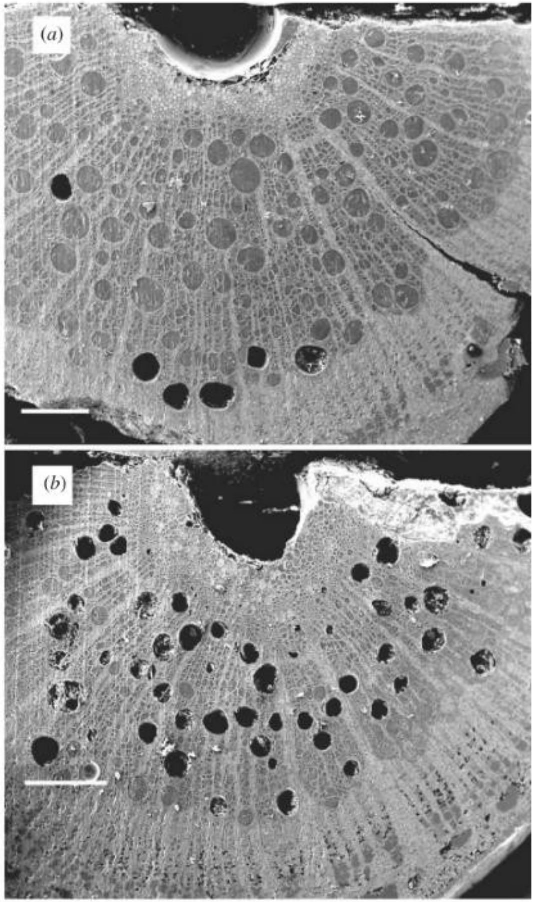
→ Reduced water store
→ Reduced conductivity
→ Reduced embolism

Janssen et al. (2020): PCE 43(4)

OPEN QUESTIONS:

- **How to measure conductivity?**
- **How often do xylem vessels need to be replaced?**
- **How expensive is embolism repair?**

Krieger et al.: Plant hydraulic conductivity experiments: EGU22-5357.html



Canny et al. (2007): Func. Plant Biol. 34(2)

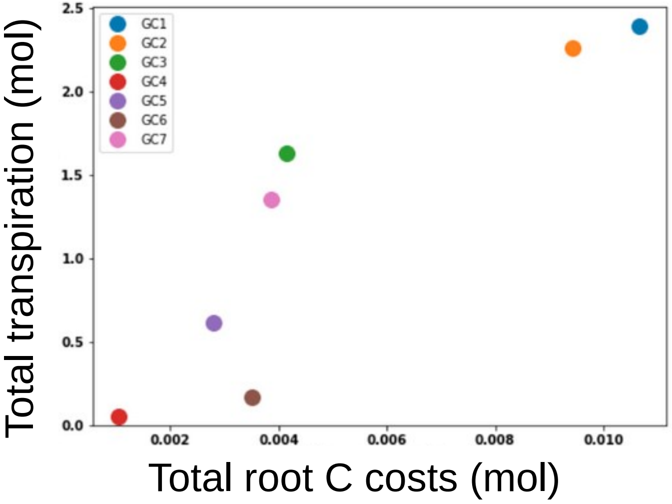
TRADE-OFFS RELATED TO ROOT UPTAKE

LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST

OPEN QUESTIONS:

- **How much C investment per water uptake?**
- **How does trade-off change with environmental conditions?**

Osuebi et al.: Shoot vs. root C flux experiments: EGU22-5798.html



CO$_2$-Adapt.

Carbon profit

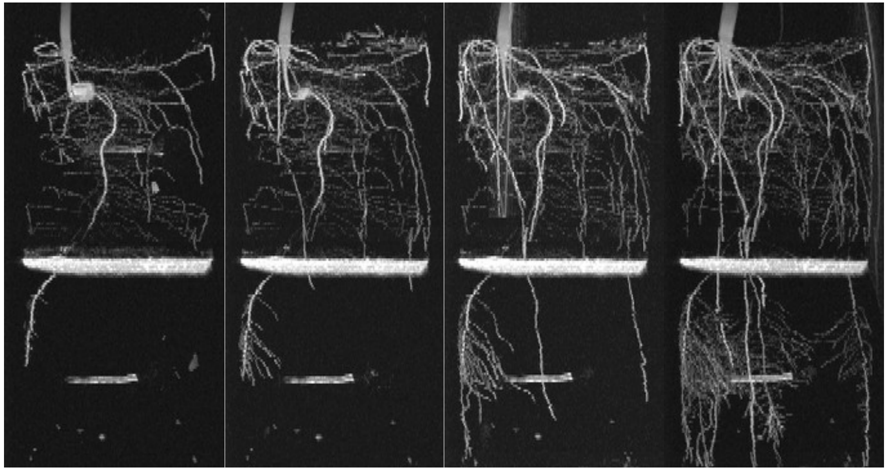
Optimality

Trade-offs

OPEN QUESTION:

- **How quickly can the root system adjust to changing environment?**

Ceolin et al.: Root system dynamics experiments: EGU22-5306.html



BG 3.4
EGU22-8841
Schymanski et al.

OPTIMALITY PREDICTS CONVERGENCE ON BUDYKO CURVE

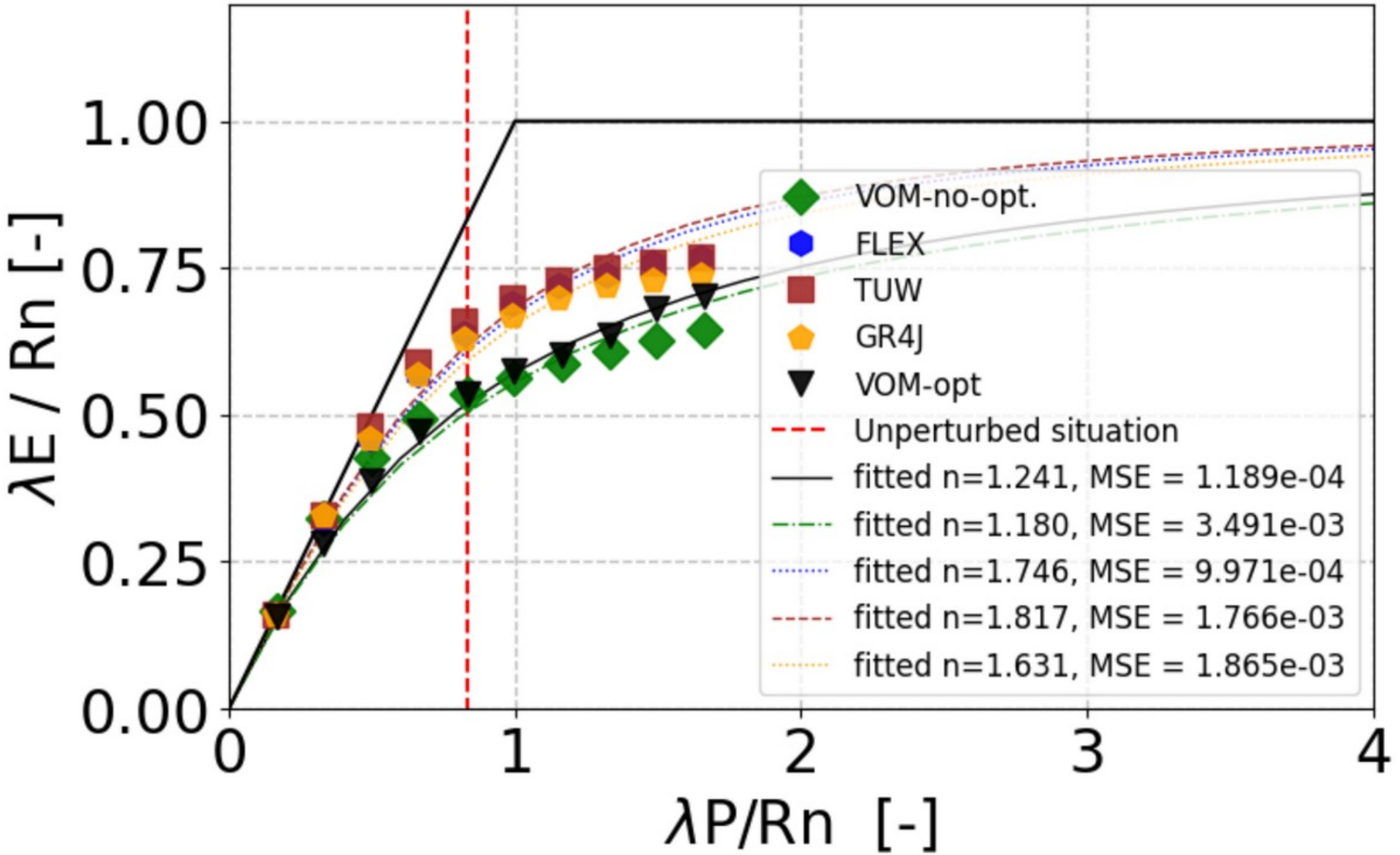
LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY
LIST

CO_2-Adapt.

Carbon profit

Optimality

Trade-offs



Nijzink, R. C., & Schymanski, S. J. (2022). HESSD 1–29.
https://doi.org/10.5194/hess-2022-97

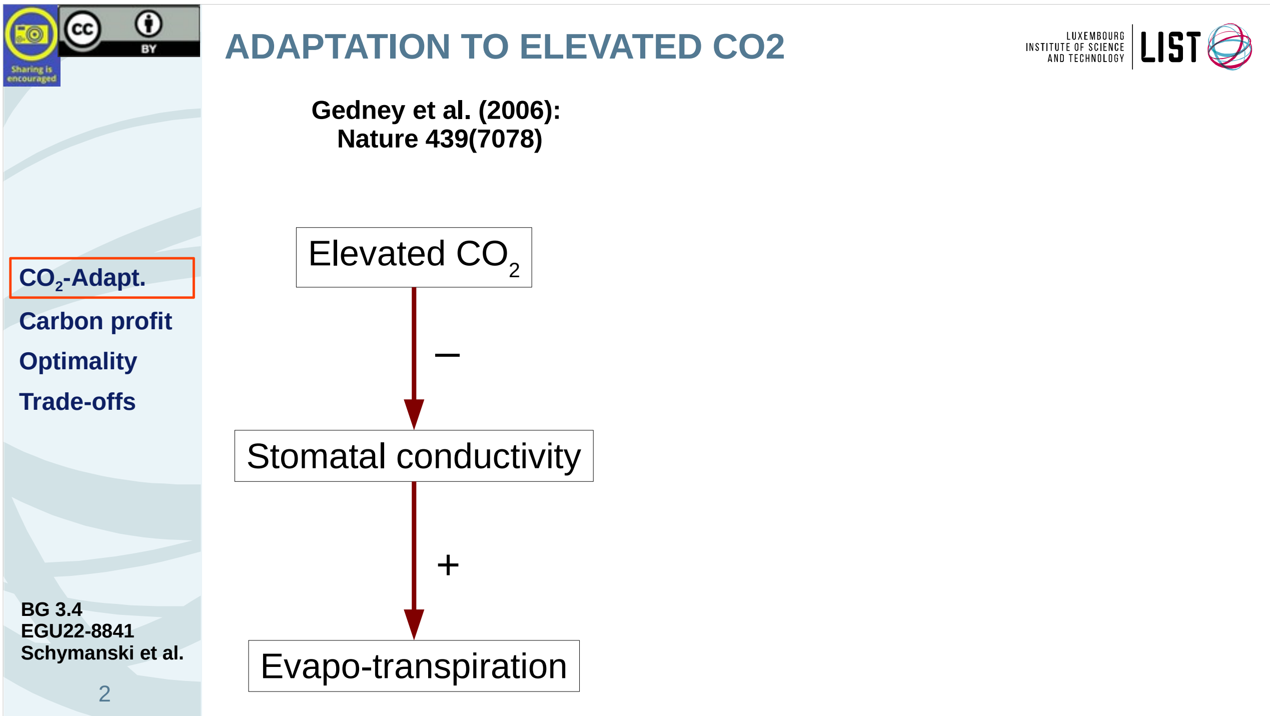
BG 3.4
EGU22-8841
Schymanski et al.

Terrestrial ecosystem responses to global change: integrating experiments and models to understand carbon, nutrient, and water cycling

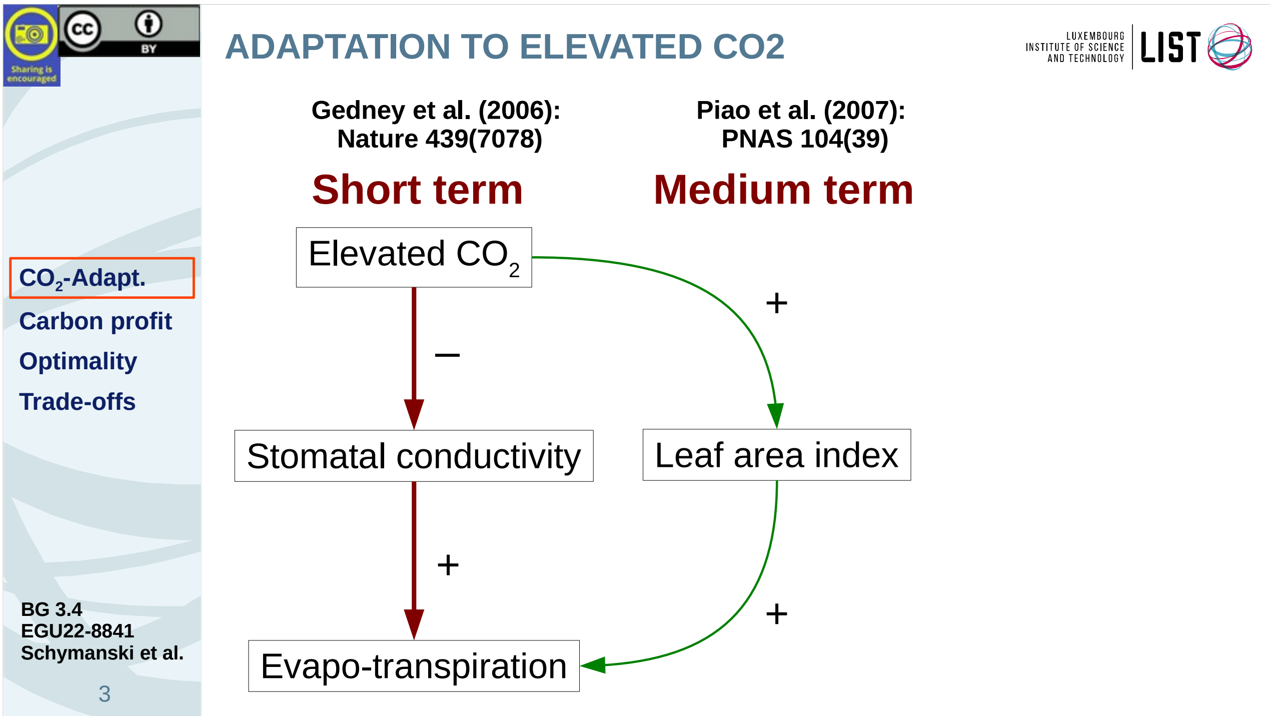
Convener: Benjamin Stocker | Co-conveners: Teresa Gimeno, Karin Rebel, Sönke Zaehle

Presentations | Fri, 27 May, 08:30–11:50 (CEST)

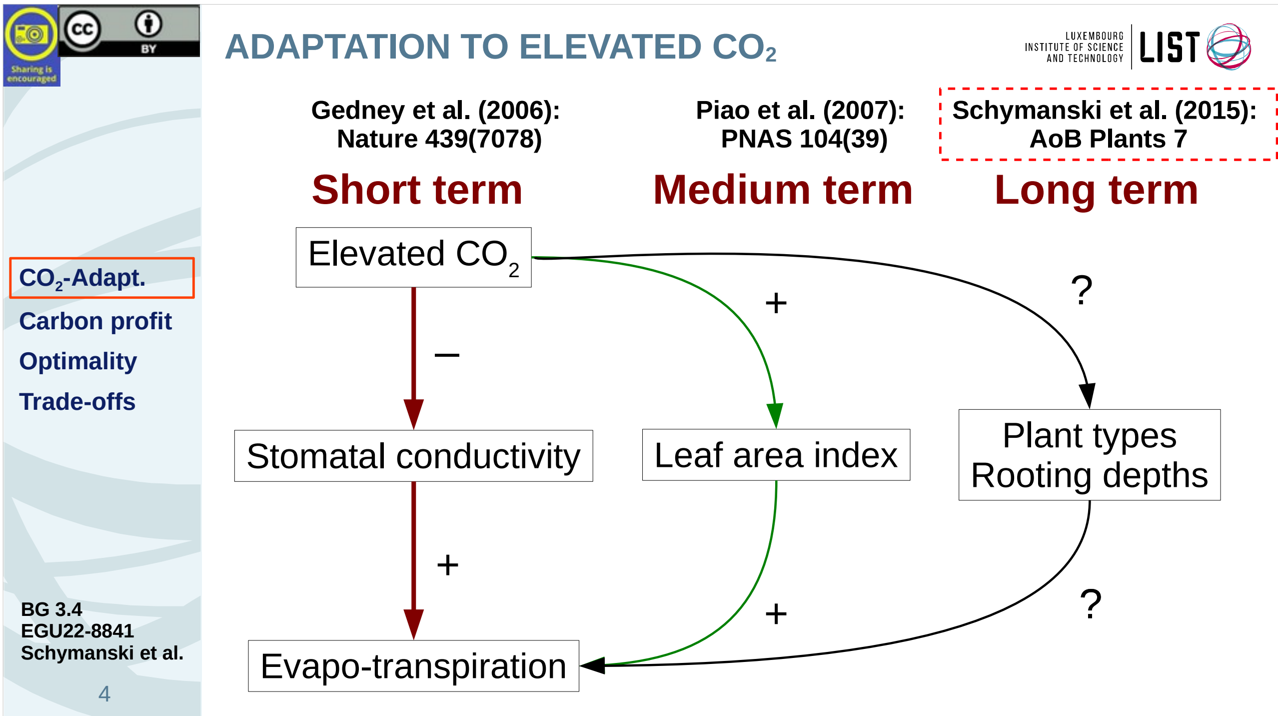
Room 3.16/17



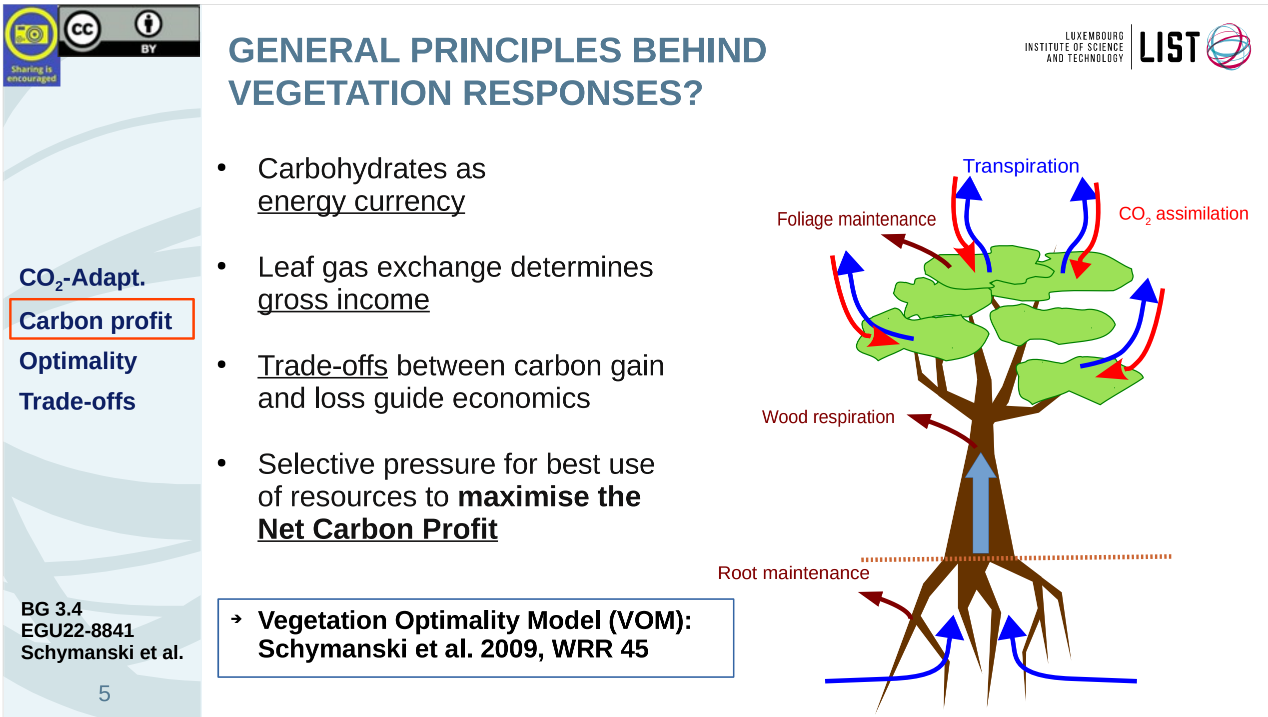
In 2006, Gedney et al. pointed out that the response of vegetation to increasing atmospheric CO2 concentrations is a reduction in ET, and likely responsible for globally increasing stream flow.



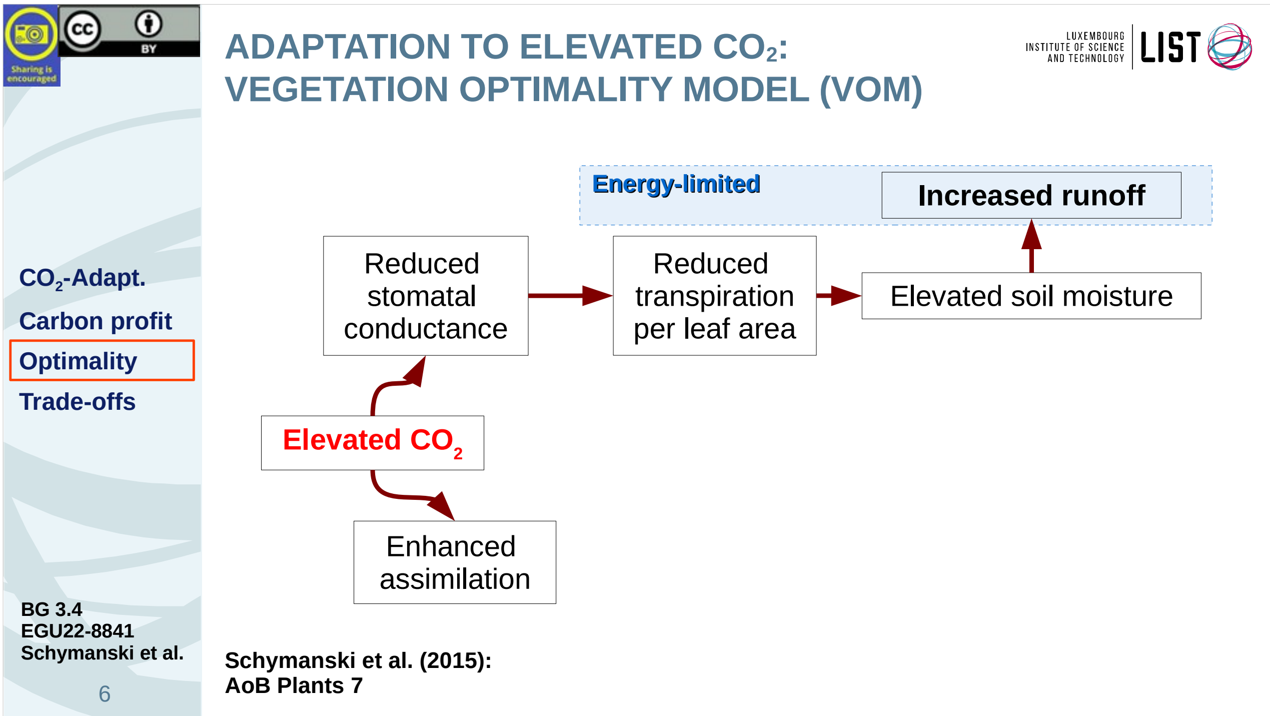
However, this response might just be a short-term effect. Piao et al. used a different model and pointed out that the reduced stomatal conductance could be compensated for by an increase in leaf area, largely negating the effect of CO2 on evapotranspiration.



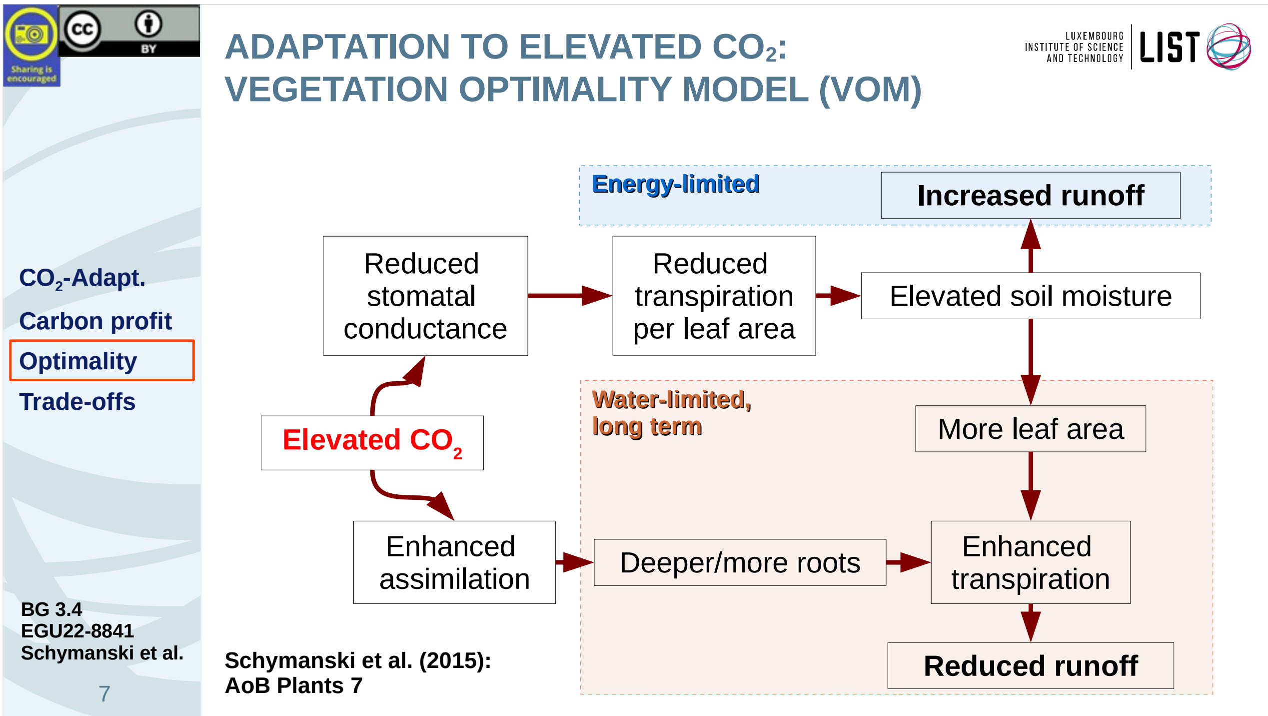
However, in the long-term, other things could change, too, such as species compositions, rooting depths etc. leading to a different net effect again. To predict such long-term responses to unseen environmental conditions, we cannot resort to past observations alone, but we need to go back to basic principles.



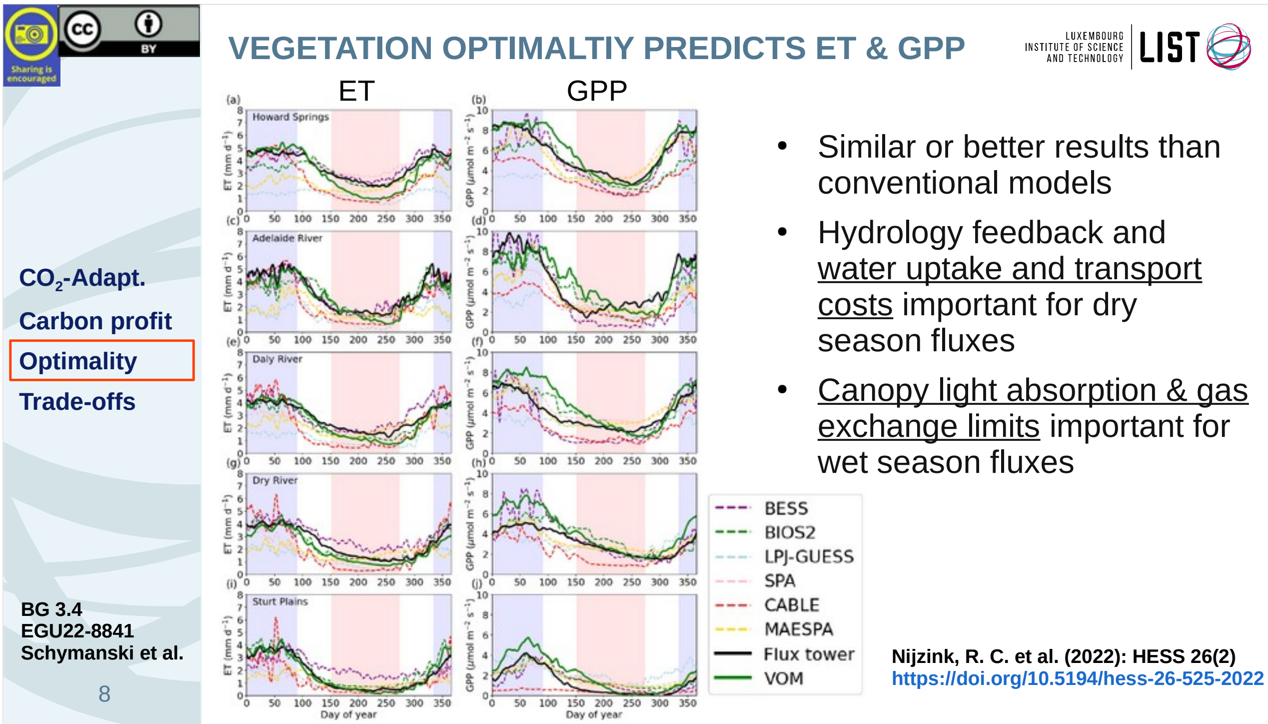
What might be the general principles guiding the adaptation of vegetation to its environment? Plants support life on our plant by using solar energy to turn CO2 into carbohydrates. If we consider carbohydrates as energy currency, we find that leaf gas exchange determines the gross income, while a lot of other plant organs assist in supplying the leaves with water and nutrients and exposing them to light. The trade-offs between carbon gain, structural investment and maintenance loss are likely to guide the adaptation to their environment. Furthermore, if there is a selective pressure for best use of resources, we could imagine that vegetation self-optimises for maximum net carbon profit. This hypothesis is the basis of the VOM, which dynamically optimises vegetation properties and water use in order to maximise the long-term NCP.



The VOM predicted that eCO2 would indeed result in enhanced assimilation and reduced transpiration in the short term, which would then result in elevated soil moisture and increased runoff. However, in the long term, this response was limited to energy-limited ecosystems. For water-limited ecosystems, elevated soil moisture allowed more plants to grow and hence resulted in increased leaf area, whereas at the same time, enhanced assimilation allowed to produce deeper or more roots, together enhancing transpiration and eventually reducing runoff. So we clearly have to distinguish between energy-limited and water-limited ecosystems, and also between short-term and long-term responses, as they can be quite opposite.



The VOM predicted that eCO2 would indeed result in enhanced assimilation and reduced transpiration in the short term, which would then result in elevated soil moisture and increased runoff. However, in the long term, this response was limited to energy-limited ecosystems. For water-limited ecosystems, elevated soil moisture allowed more plants to grow and hence resulted in increased leaf area, whereas at the same time, enhanced assimilation allowed to produce deeper or more roots, together enhancing transpiration and eventually reducing runoff. So we clearly have to distinguish between energy-limited and water-limited ecosystems, and also between short-term and long-term responses, as they can be quite opposite.



More recently, the VOM was compared with a range of established vegetation models along an aridity gradient in Australia, and it turned out that the model performed similarly or better than conventional models. Here you see the observations in black and the VOM results in green, with ET on the left and GPP in the right column. All the dashed lines refer to the other models. Please check out the paper in HESS for details. What we also learned here is that hydrology feedback and water uptake and transport costs are important for dry season fluxes, whereas canopy light absorption and gas exchange limits are important for wet season fluxes.

PROMISES AND CHALLENGES OF OPTIMALITY-BASED MODELLING

CO_2-Adapt.

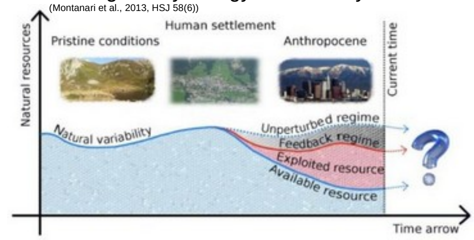
Carbon profit

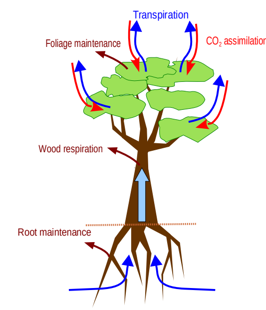
Optimality

Trade-offs

- General principles → performance in the past should indicate performance in the future
- Need to quantify physical and biological limits
- Need to quantify trade-offs between costs and benefits of carbon investments

"Change in Hydrology and Society"
(Montanari et al., 2013, HSJ 58(6))

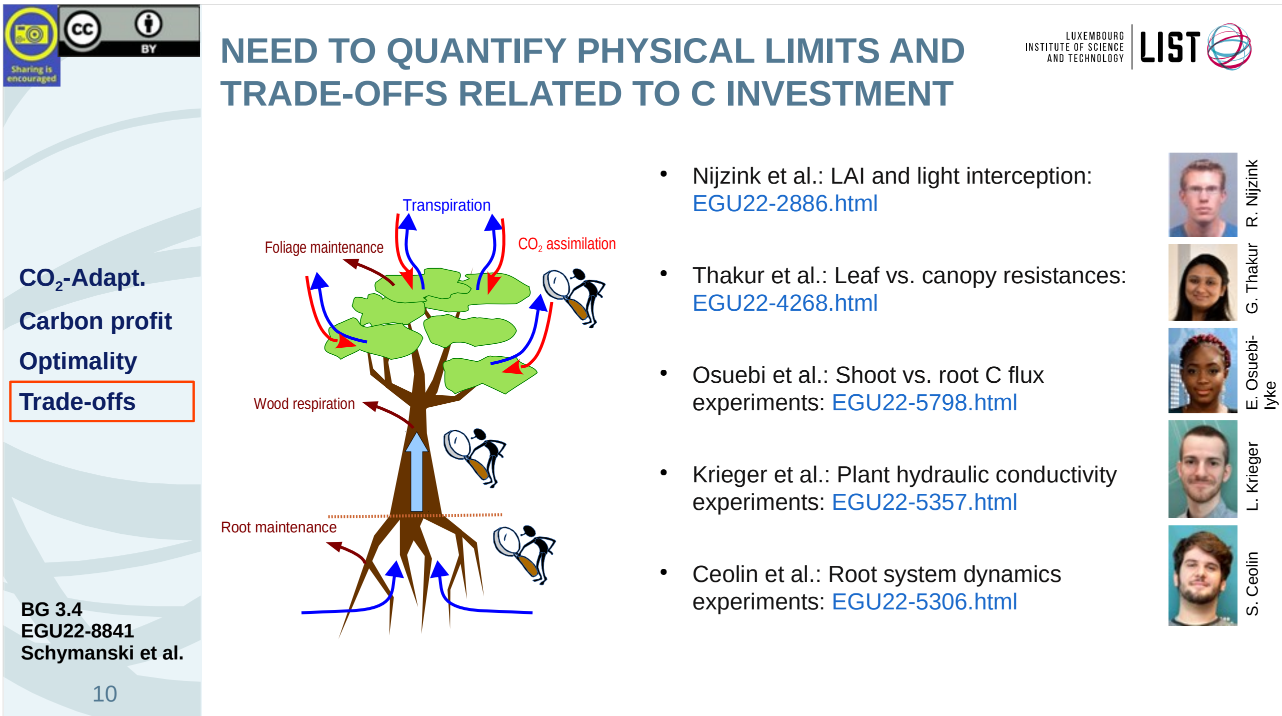




BG 3.4
EGU22-8841
Schymanski et al.

The above results highlight some of the promises of optimality-based modelling, as optimilatiy enables prediction instead of extrapolation, and therefore can be used to predict vegetation behaviour under unseen conditions. Furthermore, since it is based on a general principle, its performance in the past should be indicative of its performance in the future.

However, for the model to give meaningful results, we need to accurately quantify the physical and biological limits of plant-environment interaction, and the trade-offs between costs and benefits of carbon investments.



With this, I thank you for your interest in our work and leave you with a summary of our attempts to simulate vegetation response to change based on first principles.

APPENDIX...

CO_2-Adapt.

Carbon profit

Optimality

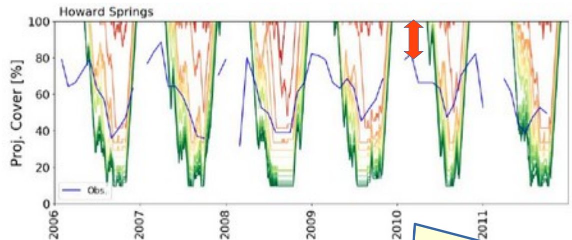
Trade-offs

BG 3.4
EGU22-8841
Schymanski et al.

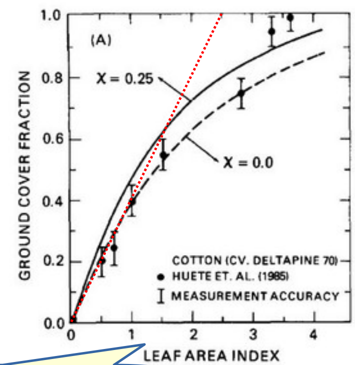
TRADE-OFFS RELATED TO LAI AND CANOPY LIGHT CAPTURING

LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST

CO_2-Adapt.
Carbon profit
Optimality
Trade-offs



Assumption in the VOM: LAI of 2.5 results in full cover (100% light interception)



Choudhury (1987): RSE 22

Why do plants waste so much leaf area instead of growing one big leaf?

Reality: cover fraction is non-linear function of LAI

BG 3.4
EGU22-8841
Schymanski et al.

Nijzink et al.: LAI and light interception: EGU22-2886.html

One problem is that the leaf turnover costs in the VOM were calculated based on the assumption that a LAI of 2.5 results in full cover. This was due to a linear extrapolation and neglect of the strong non-linearity between LAI and ground cover fraction at higher LAI values. But this makes us wonder why plants wast so much leaf area instead of growing just one big leaf.

PHYSICAL LIMITS OF CANOPY GAS EXCHANGE

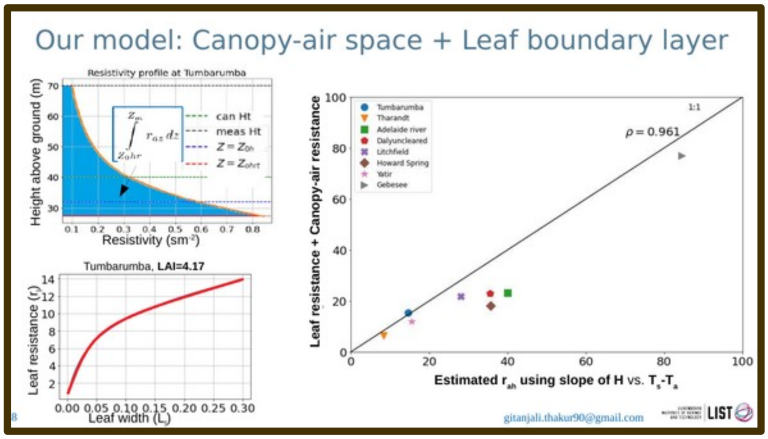
LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY LIST

CO_2-Adapt.

Carbon profit

Optimality

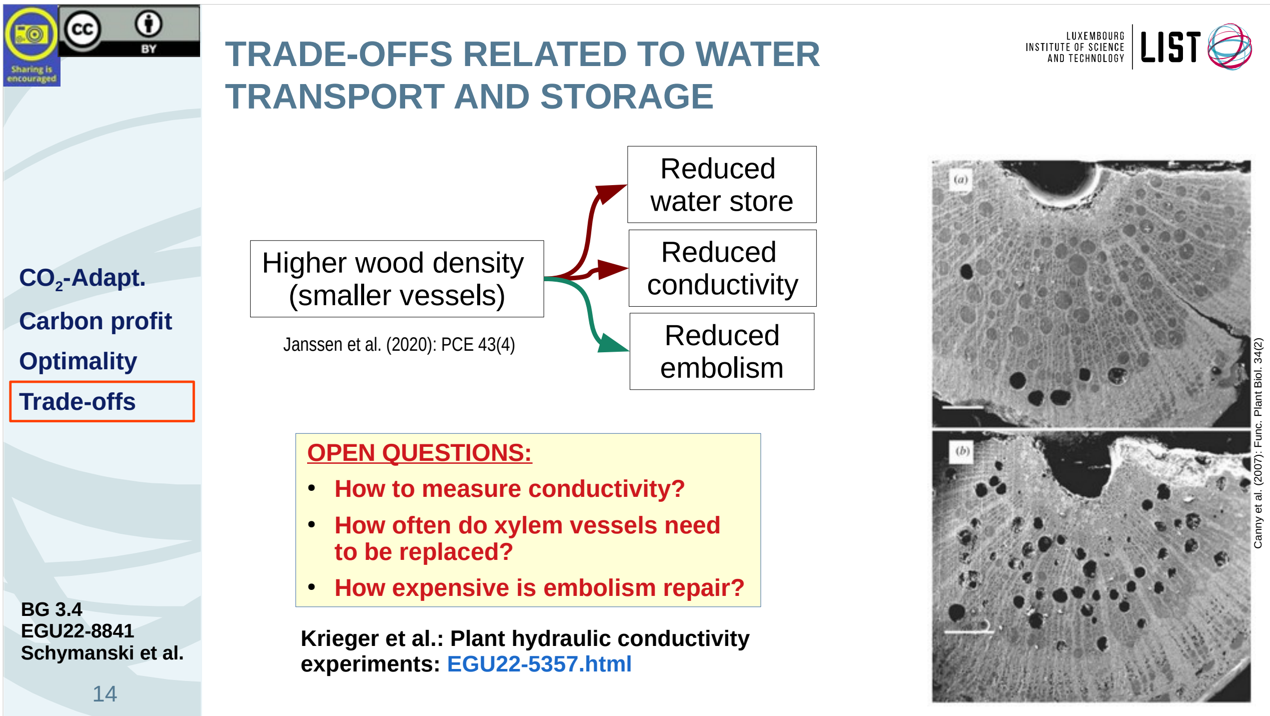
Trade-offs



Thakur et al.: Leaf vs. canopy resistances: EGU22-4268.html

BG 3.4
EGU22-8841
Schymanski et al.

This is what we set out to do in a series of research projects, two of which focus on quantifying the heat and mass transfer resistance from the leaf surface to the atmosphere, and the light interception by leaves in a canopy.



Another project investigates the trade-off between wood density or vessel size and water storage capacity, hydraulic conductivity and embolism vulnerability, where the open questions range from the basic question how to actually measure conductivity, to the longevity of xylem vessels and the carbon costs of embolism repair.

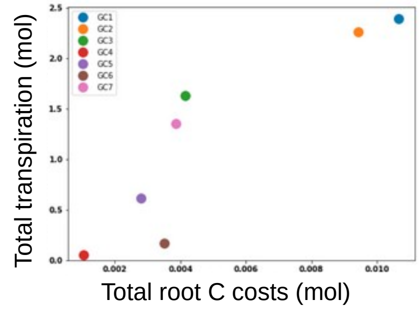
TRADE-OFFS RELATED TO ROOT UPTAKE

LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY | LIST

CO_2-Adapt.
Carbon profit
Optimality
Trade-offs

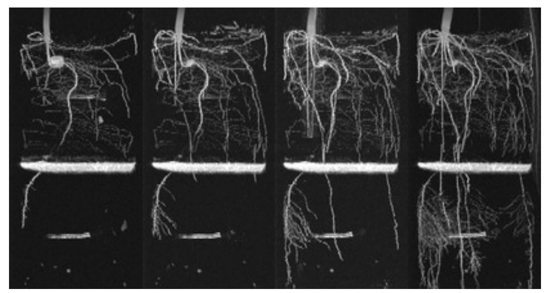
OPEN QUESTIONS:
- How much C investment per water uptake?
- How does trade-off change with environmental conditions?

Osuebi et al.: Shoot vs. root C flux experiments: EGU22-5798.html



OPEN QUESTION:
- How quickly can the root system adjust to changing environment?

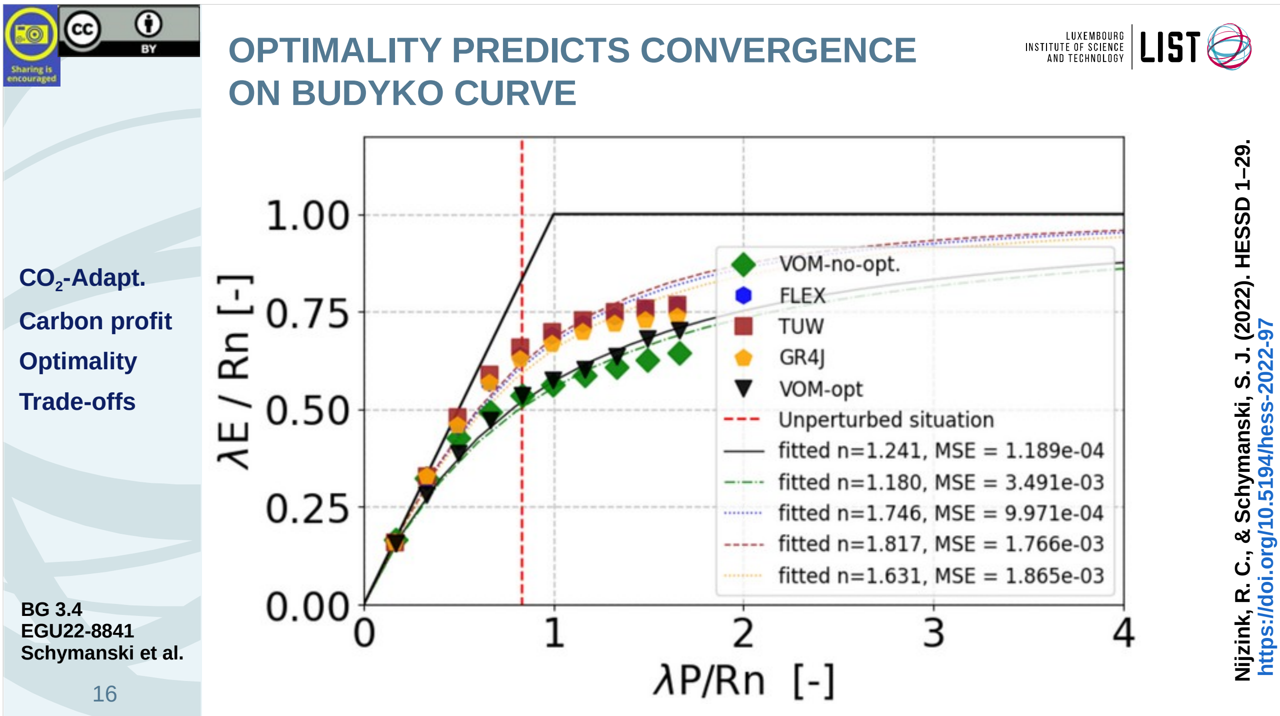
Ceolin et al.: Root system dynamics experiments: EGU22-5306.html



BG 3.4
EGU22-8841
Schymanski et al.

15

Yet another two projects focus on the trade-off between root c investment and maintaining a given water uptake capacity under different environmental conditions, and how quickly roots can actually adapt to a changing environment.



Another interesting result of the Vegetation Optimality Model is that it explains response of vegetation water use to changes in precipitation. Catchments world-wide follow the empirical Budyko curve and it is commonly assumed that the response of ET to changes in climate can be simulated by moving a catchment along its own Budyko curve. In a recent paper in HESSD, we found that only if vegetation is allowed to optimally adjust to each new precipitation setting, the catchment does indeed move along the Budyko curve, otherwise the sensitivity to rainfall is smaller than the empirical curve.