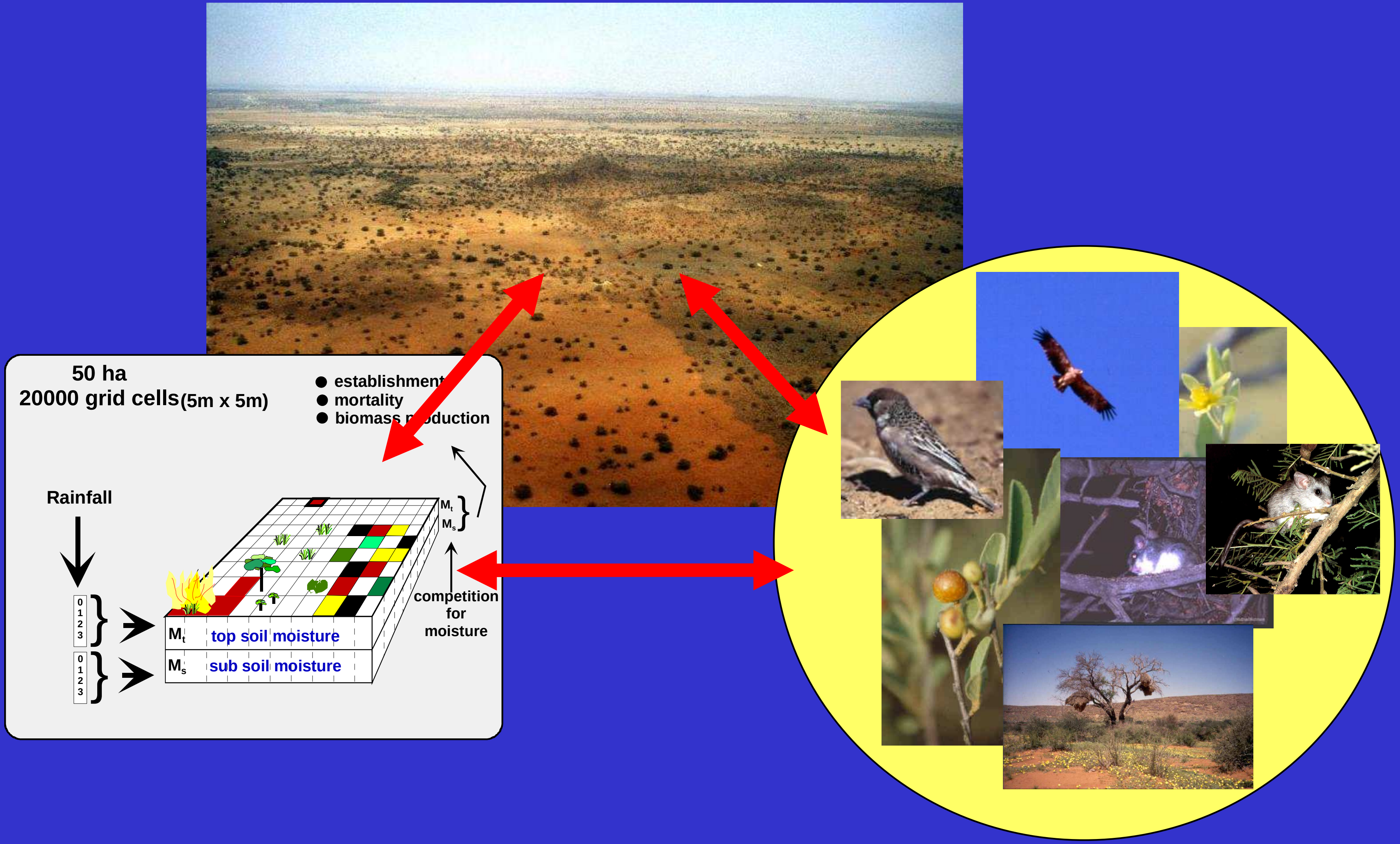
Simulating savanna dynamics: from system stability to biodiversity

Florian Jeltsch, University of Potsdam



50 ha

20000 grid cells (5m x 5m)

- establishment
- mortality
- biomass production

Rainfall

top soil moisture

sub soil moisture

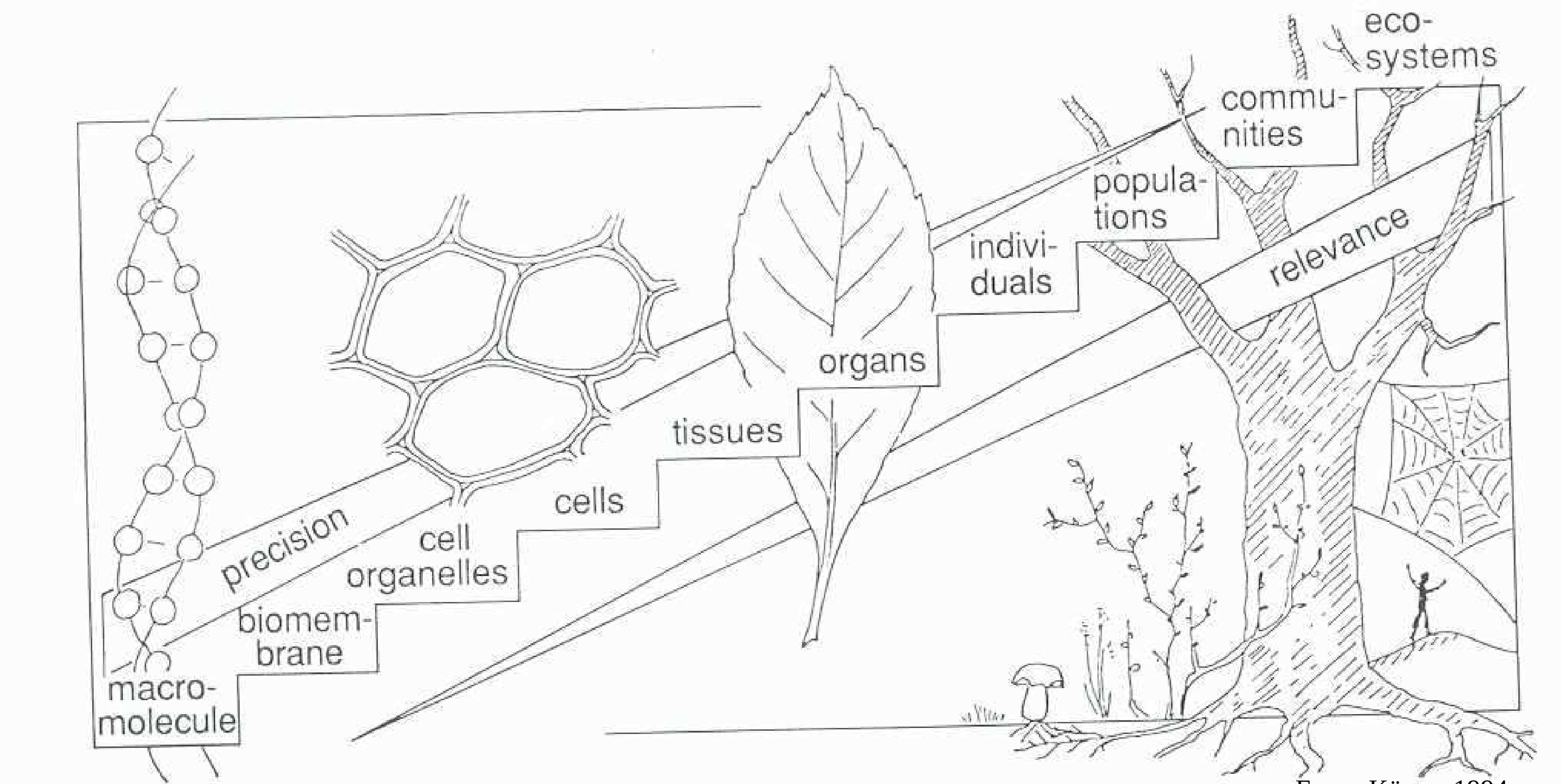
competition for moisture

Ecological systems are complex

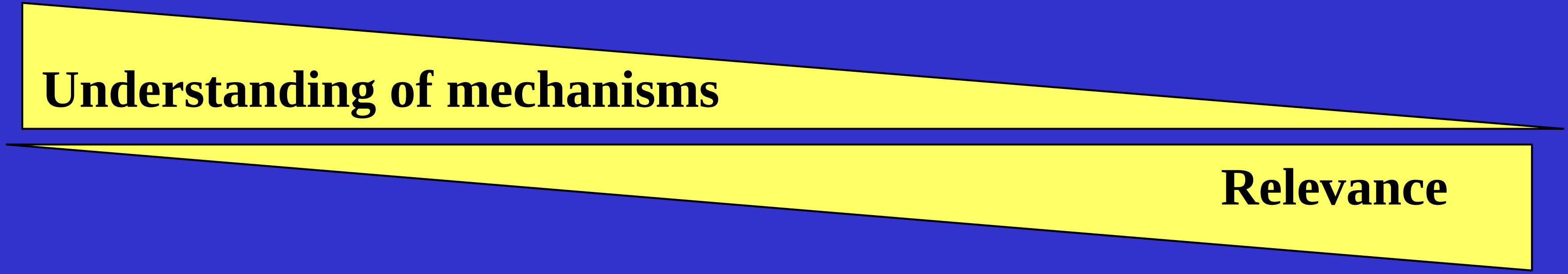
- Sub-individual level (genetics, physiology, …)
- **Individuals** (variability, adaptation, behaviour, …)
- Communities (+ and - interactions, …)
- Variability/Stochasticity in space and time (climate, ‚landscapes‘, hydrology, soil, …)
- Anthropogenic influence (use, management, destruction, ..)
- ….

Ecology also has a scaling problem

Bottom-Up versus Top-Down?



From: Körner 1994



Understanding of mechanisms

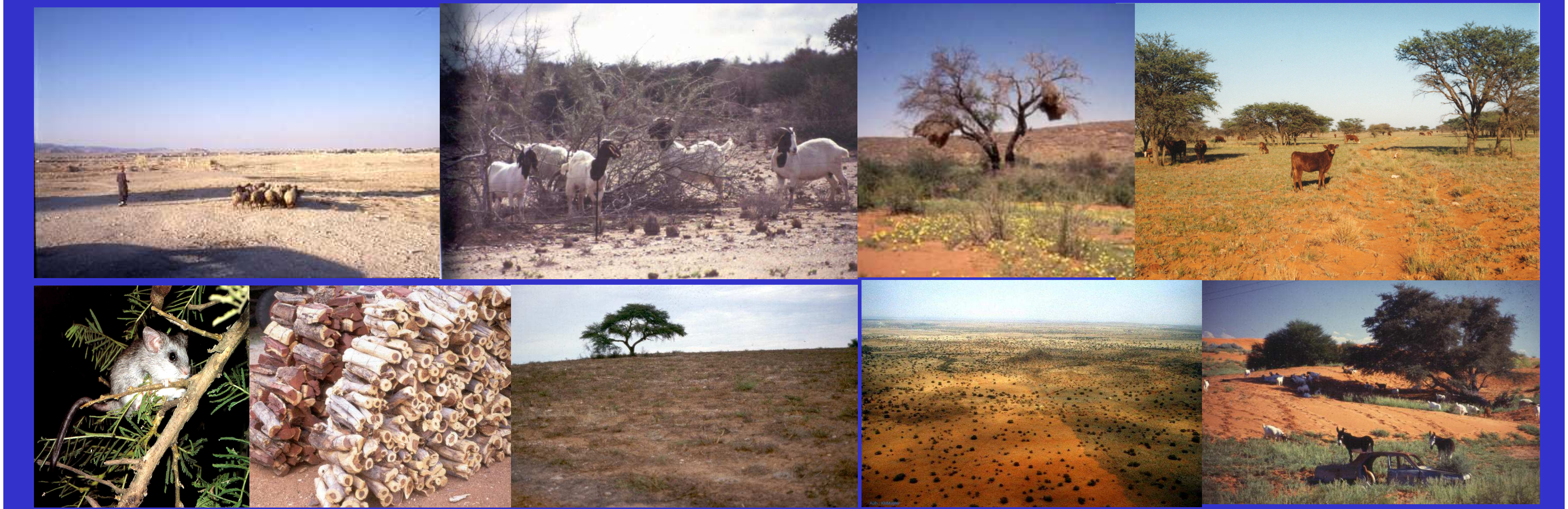
Relevance

How can we analyze ecologcial systems?

- Experiments (sufficient replications difficult, long time scales difficult, spatial aspects problematic)
- Models (often necessary: stochastic, spatially-explicit, individial/agent-based)
- General theory in ecology is (still) sparse

Example: Savannas

- Savannas: approx. 20% of land surface
- variety of climatic (<100 – 1500 mm) and edaphic conditions
- problems: climate change, land use, desertification



Overview

I. Savanna stability

II. Savanna biodiversity

- Impact of land use
- Impact of climatic changes
- (Very) brief Outlook

Conclusion

I. Savanna stability

- The savanna question: ‘What is special about the savanna environment that allows trees and grasses to coexist, as opposed to the general pattern in other areas of the world where either one or the other functional type is dominant?‘ (Sarmiento 1984)

Why not either woodland or grassland????

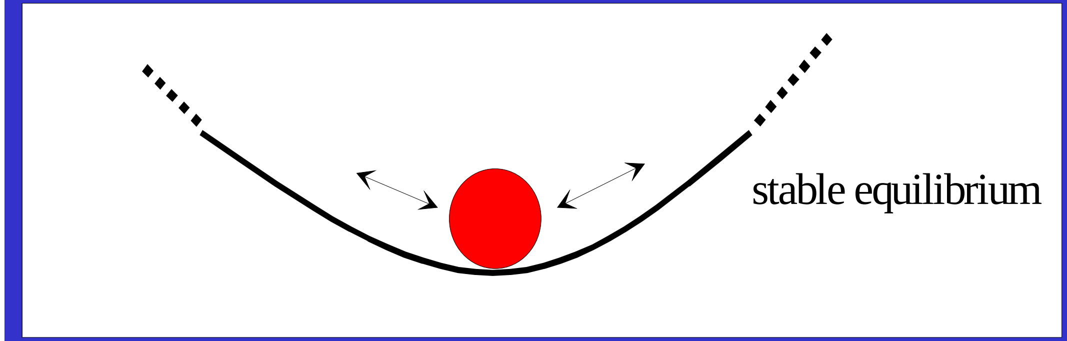
Savanna stability

Hypothesis 1 (non-spatial models, ‘two layer hypothesis‘)

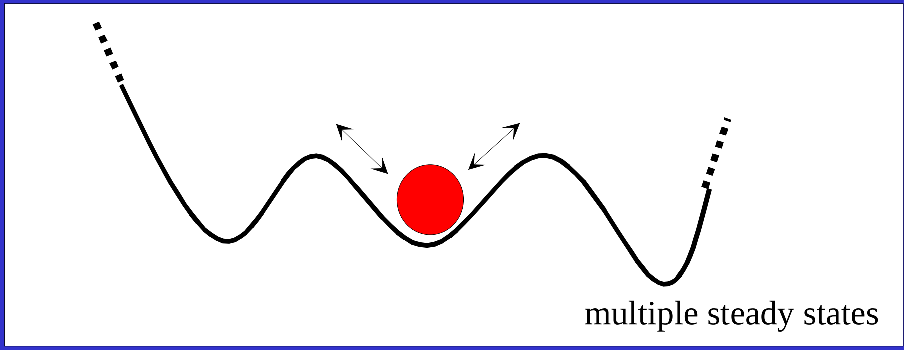
(Walker & Noy-Meir 1982, Eagleson 1985, Skarpe 1992,..)

Competition for soil moisture:

- **niche separation in the root layer, i.e. grass roots take water from upper soil layer, tree roots from lower soil layer**



or



assumptions rejected by field studies

Savanna stability

Hypothesis 2

(Scholes and Walker 1993, ...)

Inherently unstable mixture of trees and grasses which persists owing to large scale disturbances:

- fire and grazing

→ We need a spatial point of view

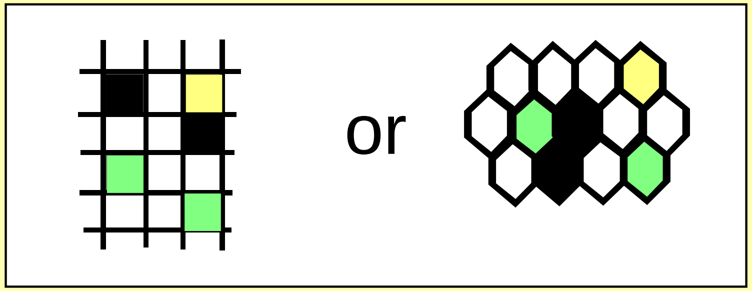
Approach: grid-based simulator (extended cellular automata)

- Ideal tool for stochastic, spatially-explicit simulations

Grid-based simulation models

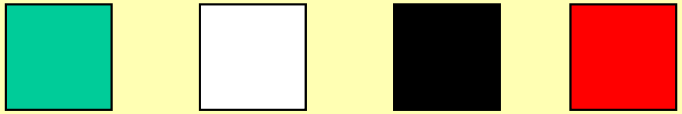
1. Discrete in space
Space subdivided in grid of ‘cells’

(plant parts, individuals, range of interaction, range of seed dispersal, sampling plots, ..)



2. Discrete in time
Limited number of ecological states

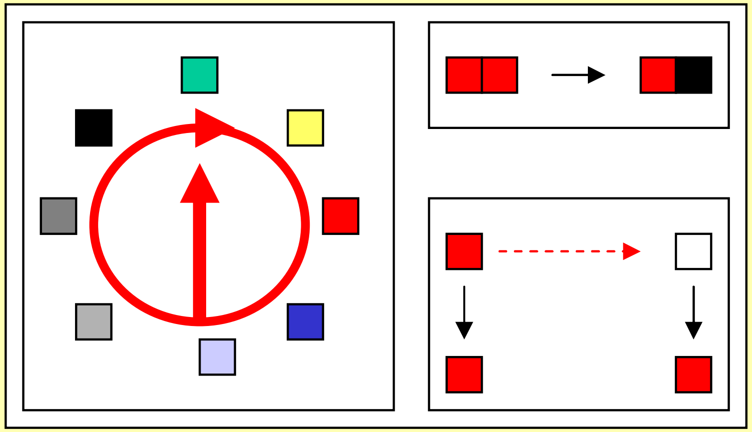
(age, size, number of individuals, phase in succession, ...)



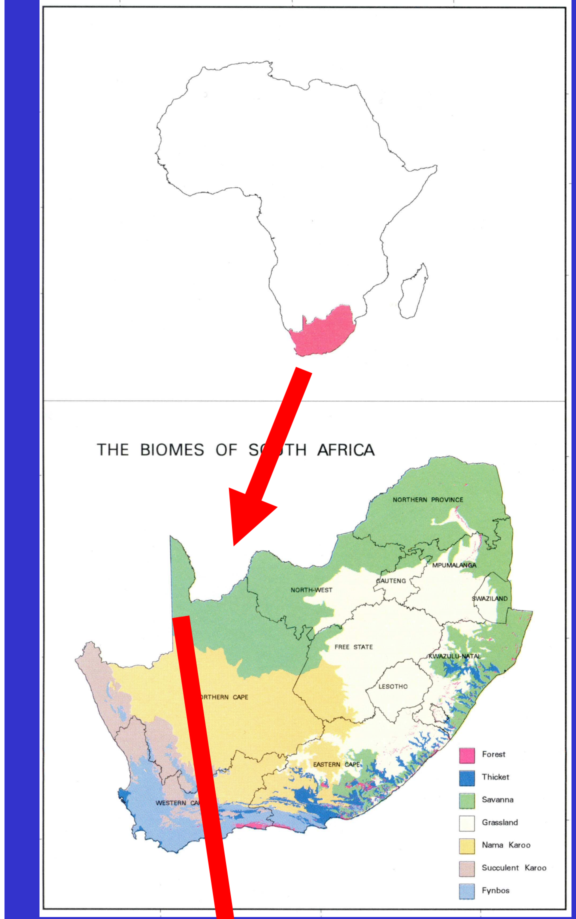
3. Changes of state

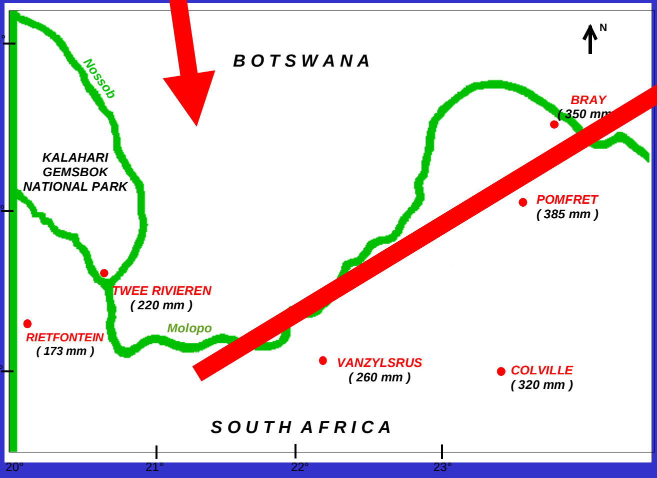
Set of ecological rules → **math. equations** / → **verbal rules**

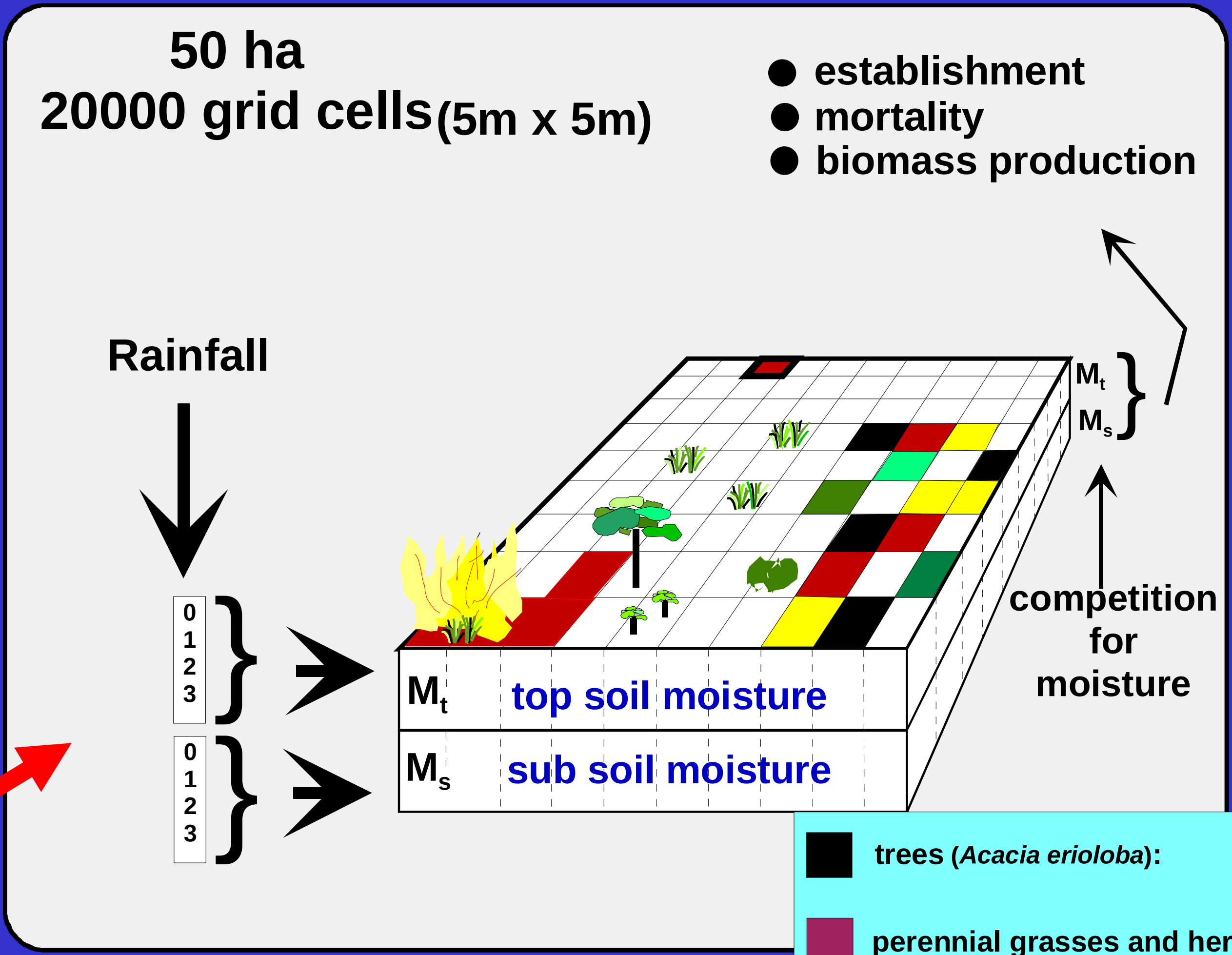
(local dynamics, neighbourhood interactions, external forces)



Grid-based savanna model







50 ha

20000 grid cells (5m x 5m)

- ● establishment
- ● mortality
- ● biomass production

Rainfall

0
1
2
3

0
1
2
3

M_t top soil moisture

M_s sub soil moisture

M_t

M_s

competition for moisture

- ⬛ trees (*Acacia erioloba*):
- 🟥 perennial grasses and herbs (e.g. *Stipagrostis obtusa*)
- 🟩 shrubs (e.g. *Rhigozum trichotomum*)
- 🟨 annuals (e.g. *Schmidtia kalahariensis*)
- 🟩 mix
- ⬜ empty

Basis: 30 years of empirical research (v. Rooyen et al.)

Savanna stability

Hypothesis 2

(Scholes and Walker 1993, ...)

Inherently unstable mixture of trees and grasses which persists owing to large scale disturbances:

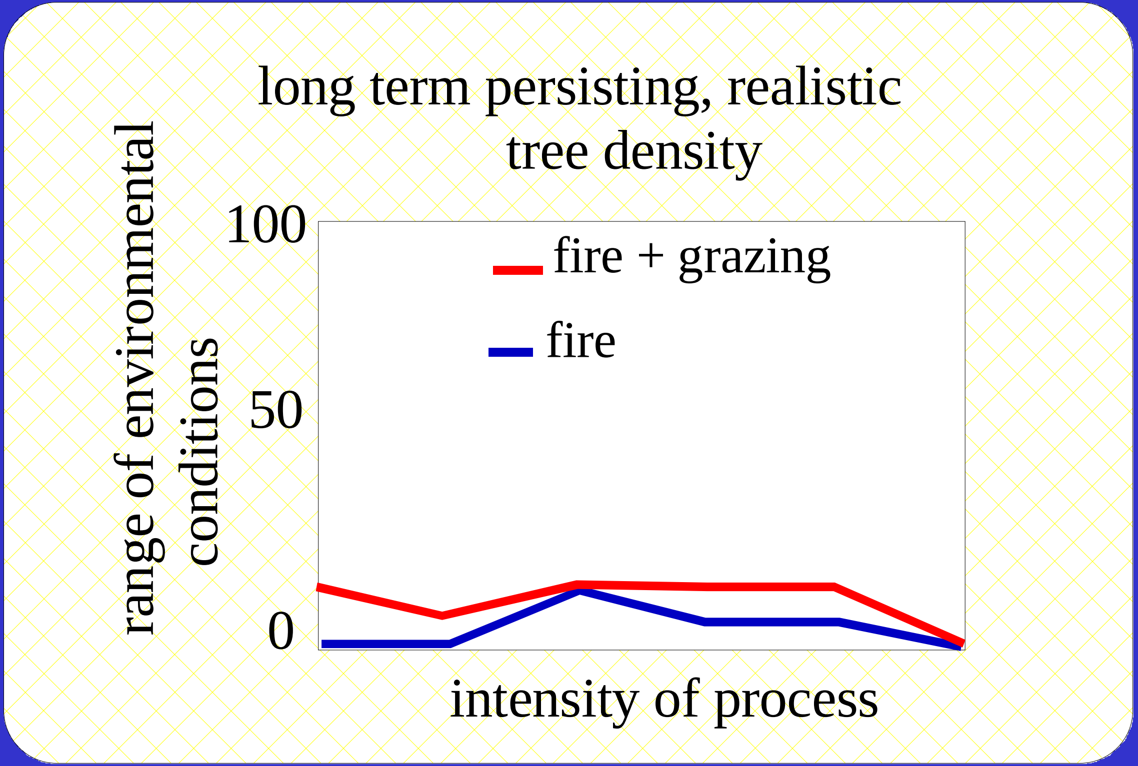
- fire and grazing

Spatial savanna model

Savanna stability

Results hypothesis 2: Coexistence can occur BUT:only narrow range of environmental conditions with tree-grass coexistence and realistic tree densities

(Jeltsch et al., J.Ecol., 1996)

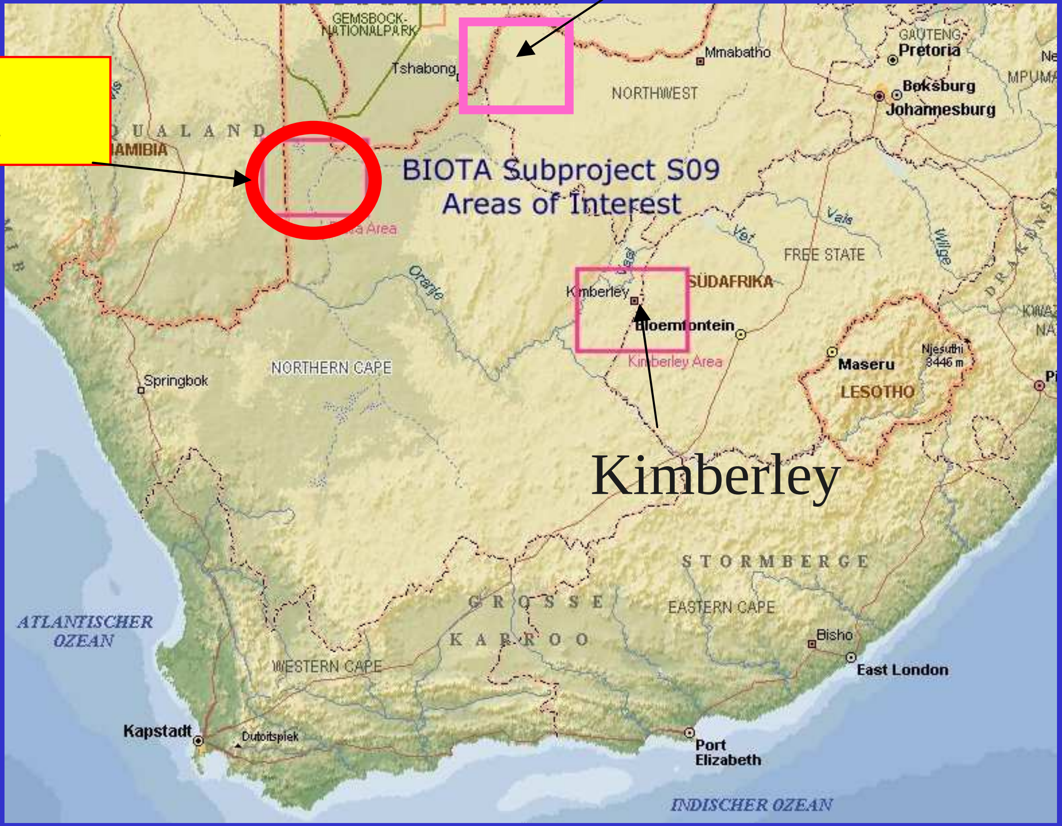


Realistic tree distribution/pattern??

Test-location: Savanna - southern Kalahari

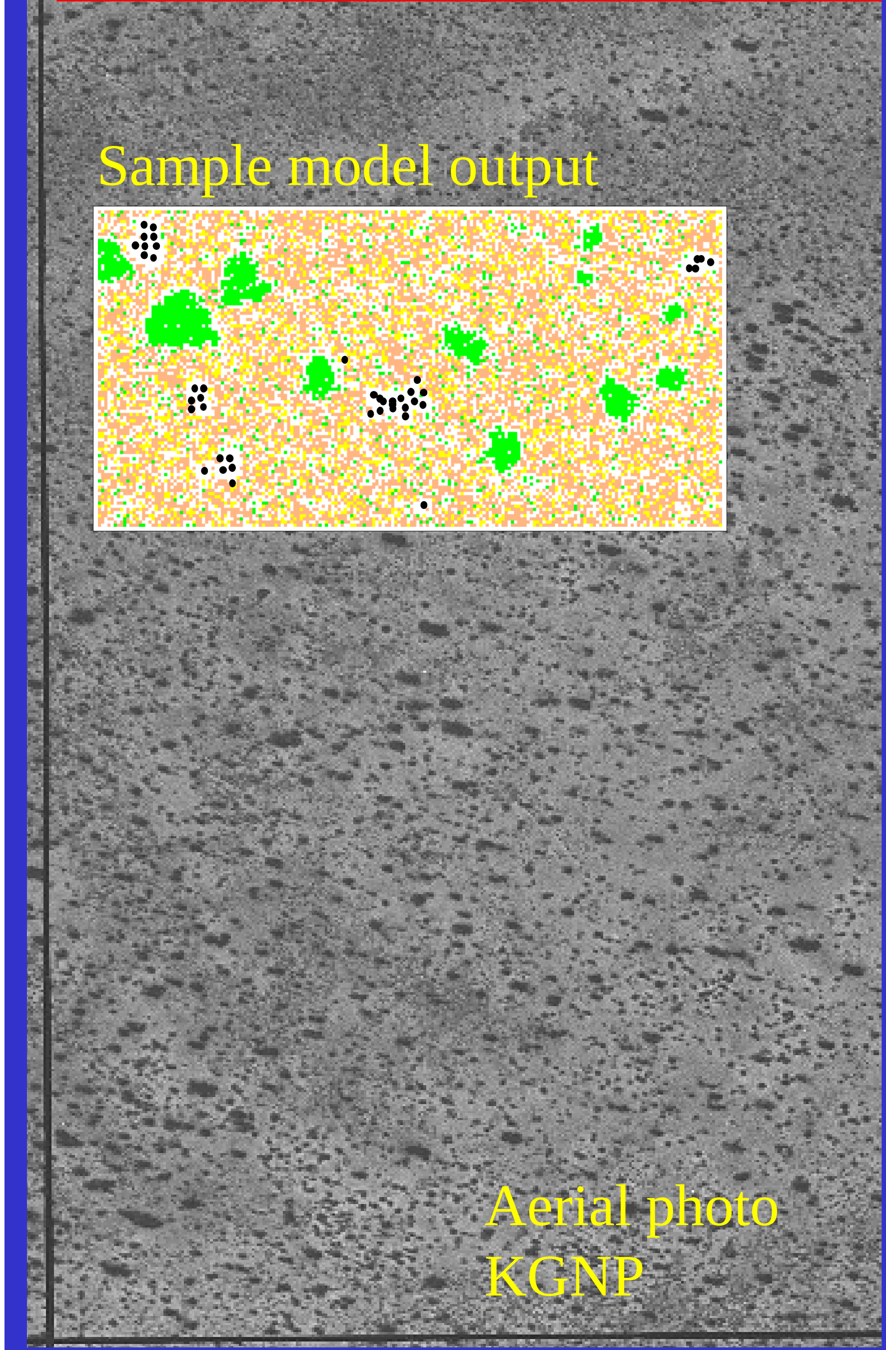
Molopo

Focal area



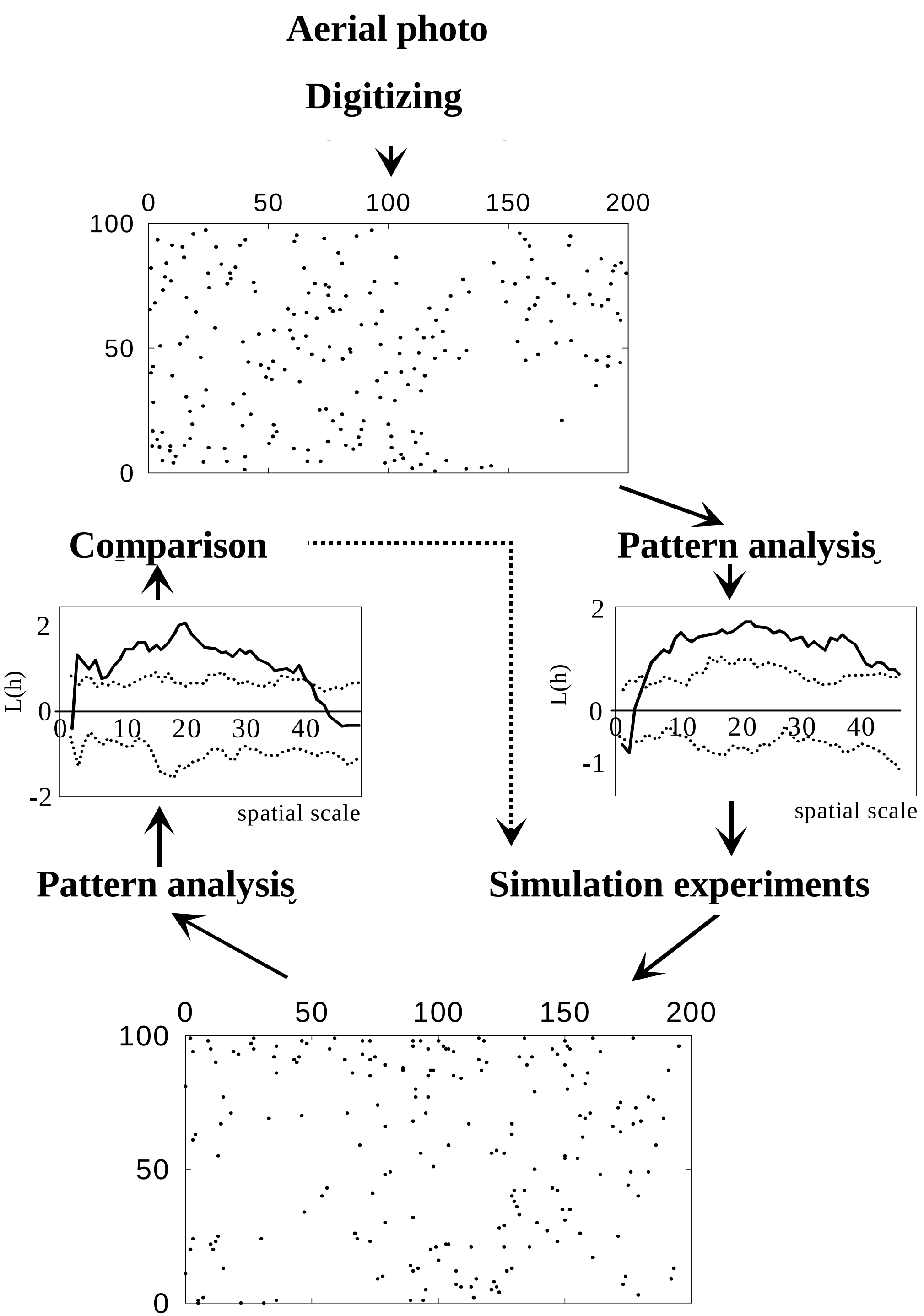
Kimberley

Understanding process and pattern with spatial models:



Sample model output

Aerial photo
KGNP



Aerial photo

Digitizing

Pattern analysis

Simulation experiments

Pattern analysis

Comparison

Savanna stability

Results hypothesis 2: Unrealistic tree distribution at realistic tree densities

(unrealistic high clumping at small scales => tree patches)

Savanna stability

Hypothesis 3 (Kalahari):

Additional process: formation of microsites (small-scale heterogeneities) that furnish better establishment conditions for tree seedlings

- ➢ e.g. patchy seed dispersal in herbivory dung, termite heaps, animal diggings,...

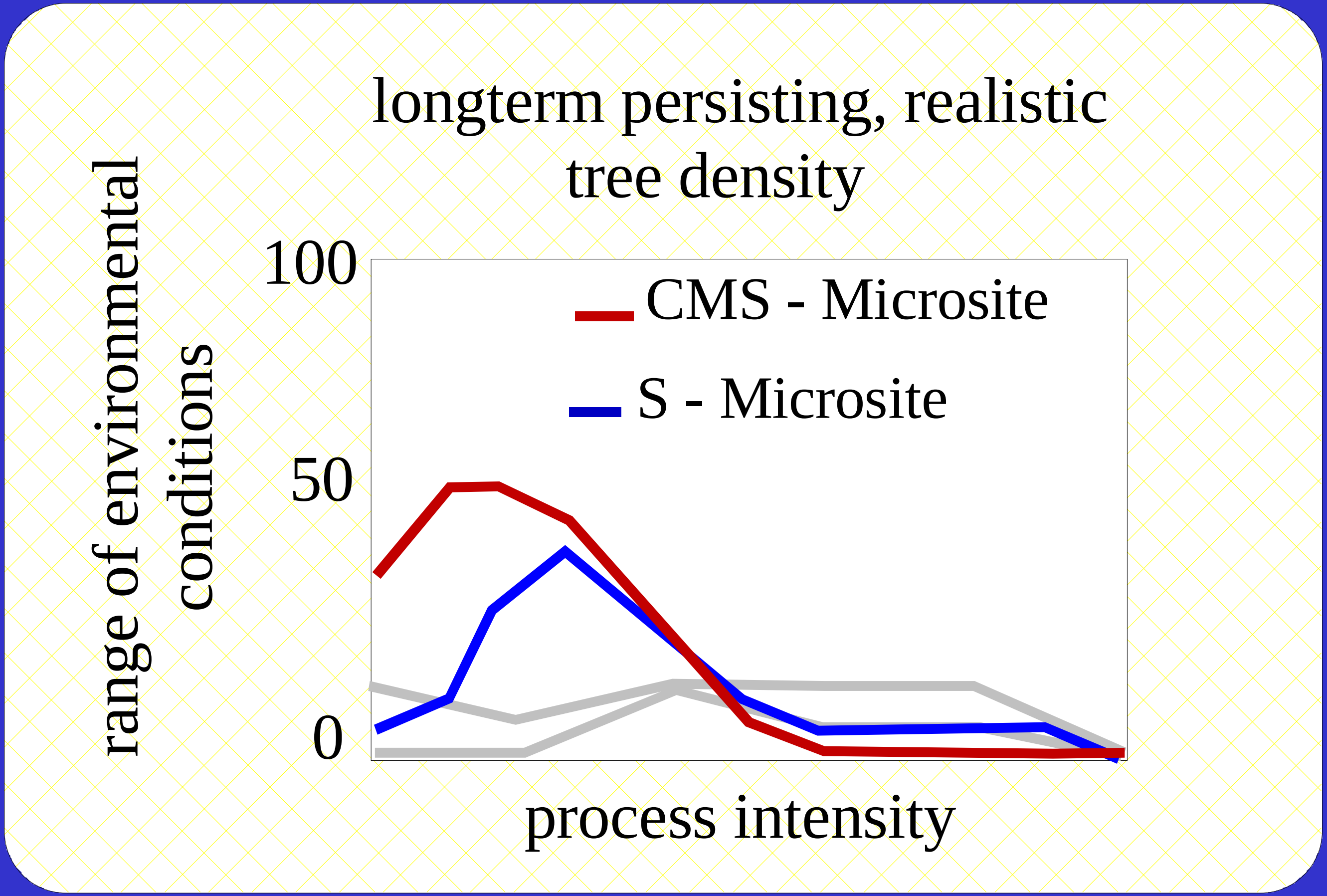
→

field studies in the KGNP 1997:
significantly higher tree seedling density in microsites, especially in dung-patches (Jeltsch et. al., J. Ecol, 1998)

Savanna stability

Results hypothesis 3 (Kalahari): Increased range of environmental conditions with realistic tree density

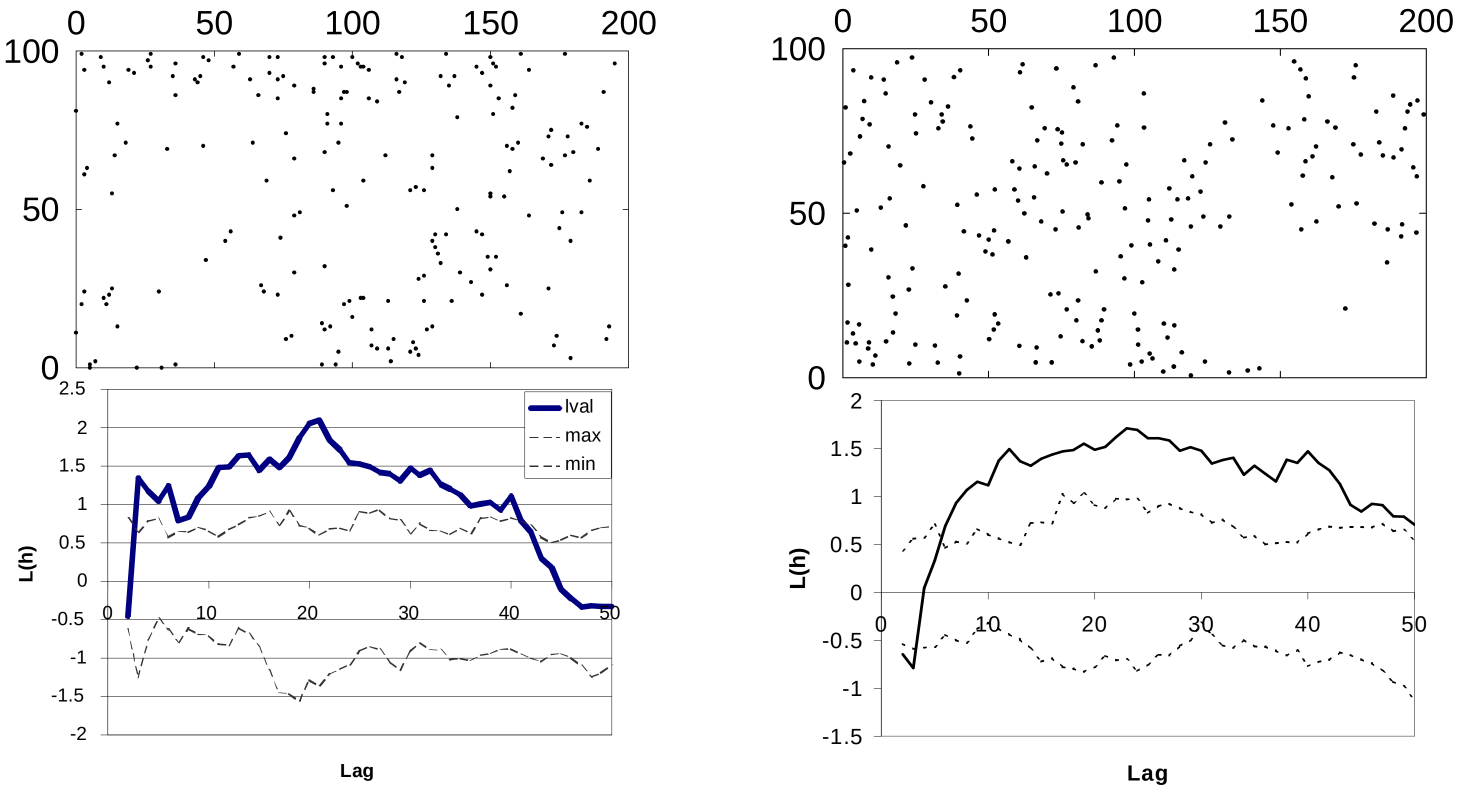
(Jeltsch et al. 1998)



Savanna stability

Results hypothesis 3 (Kalahari): (Jeltsch et al. 1998)

realistic, non-random tree distribution at realistic tree densities

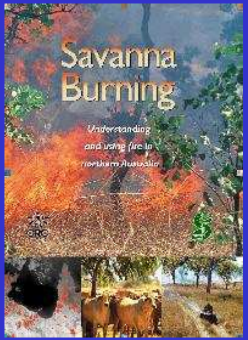


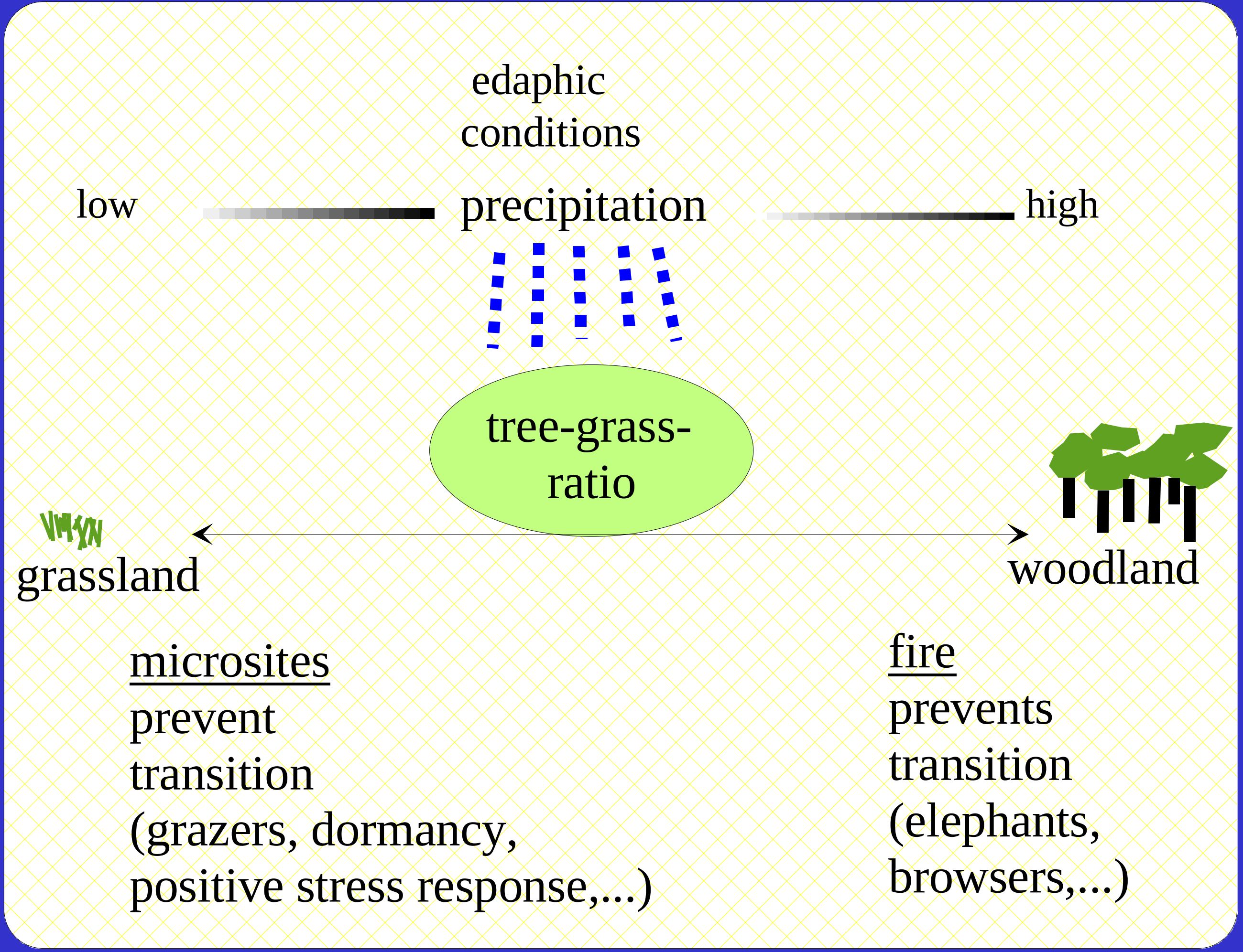
model (hypothesis III)

real (KGNP)

More general:

Savannas do not present a stable mixture of trees and grasses but an inherently unstable mixture which persists owing to buffering mechanisms that prevent the transition of system boundaries





edaphic conditions

low precipitation high

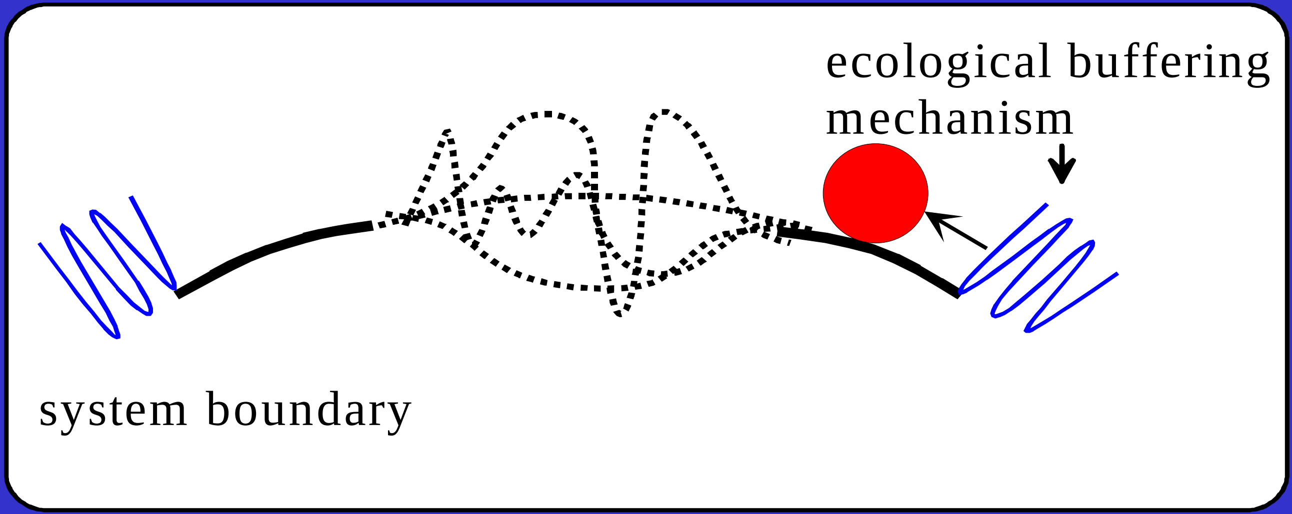
tree-grass-ratio

grassland

woodland

microsites prevent transition (grazers, dormancy, positive stress response,...)

fire prevents transition (elephants, browsers,...)



ecological buffering mechanism

system boundary

II. Savanna biodiversity

(= diversity of species (inc. genetics), habitats etc.)

Spatial vegetation structure (= structural diversity) determines biodiversity and ecological processes

- Single trees as hotspots of biodiversity

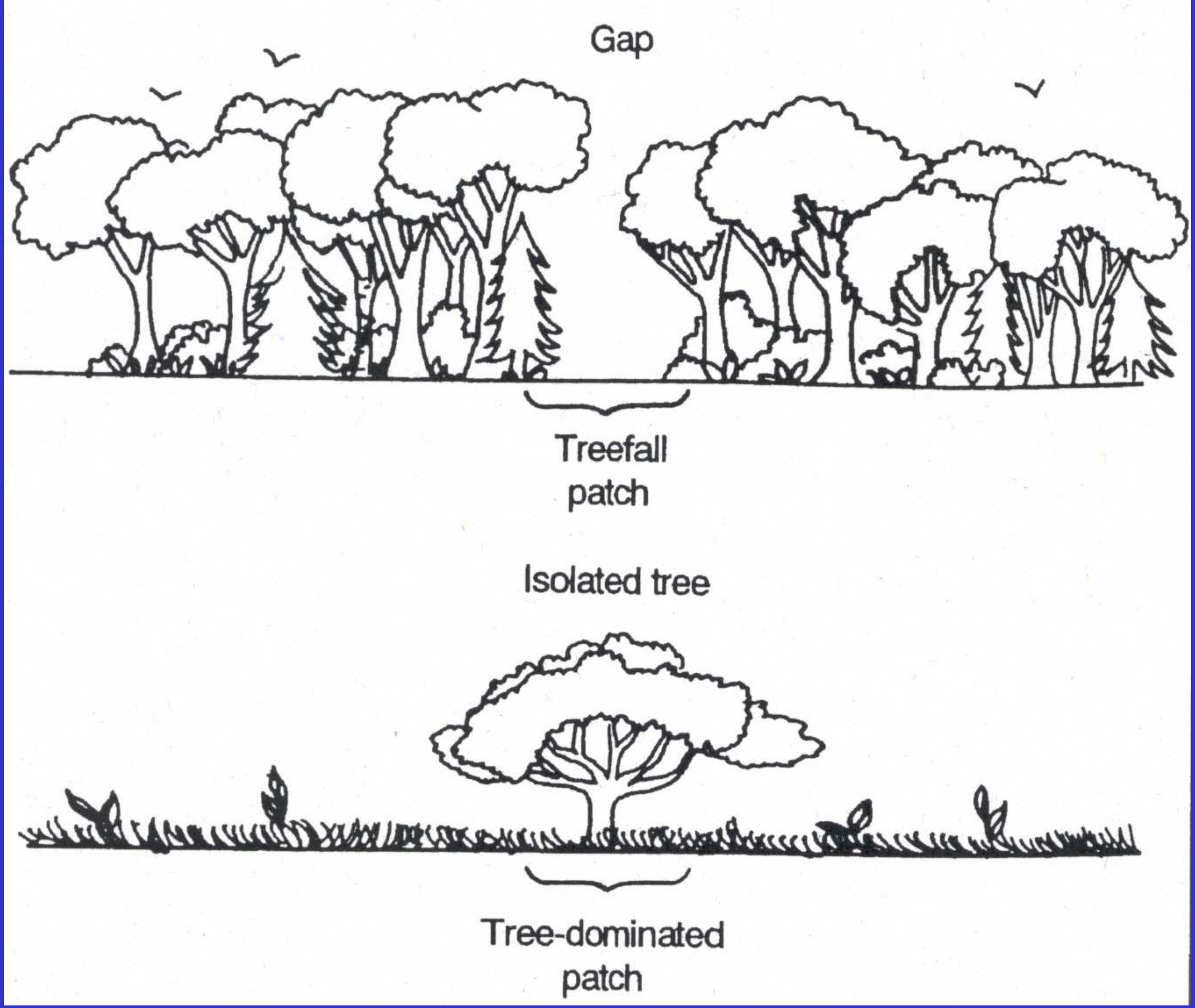
- Shrub encroachment caused by overgrazing: risk for biodiversity

Isolated trees as diversity hotspots

Dean et al. 99, Belsky et al.89, 93,..)

- Shadow, nesting, roosting, ...
- Nutrient input, soil moisture increased, seed input
- Specific vegetation

Isolated trees in savannas `=` trees gaps in tropical forests



BIOTA study: What is the impact of land use and climatic changes on structural and species diversity in the southern Kalahari?

Socio-economy

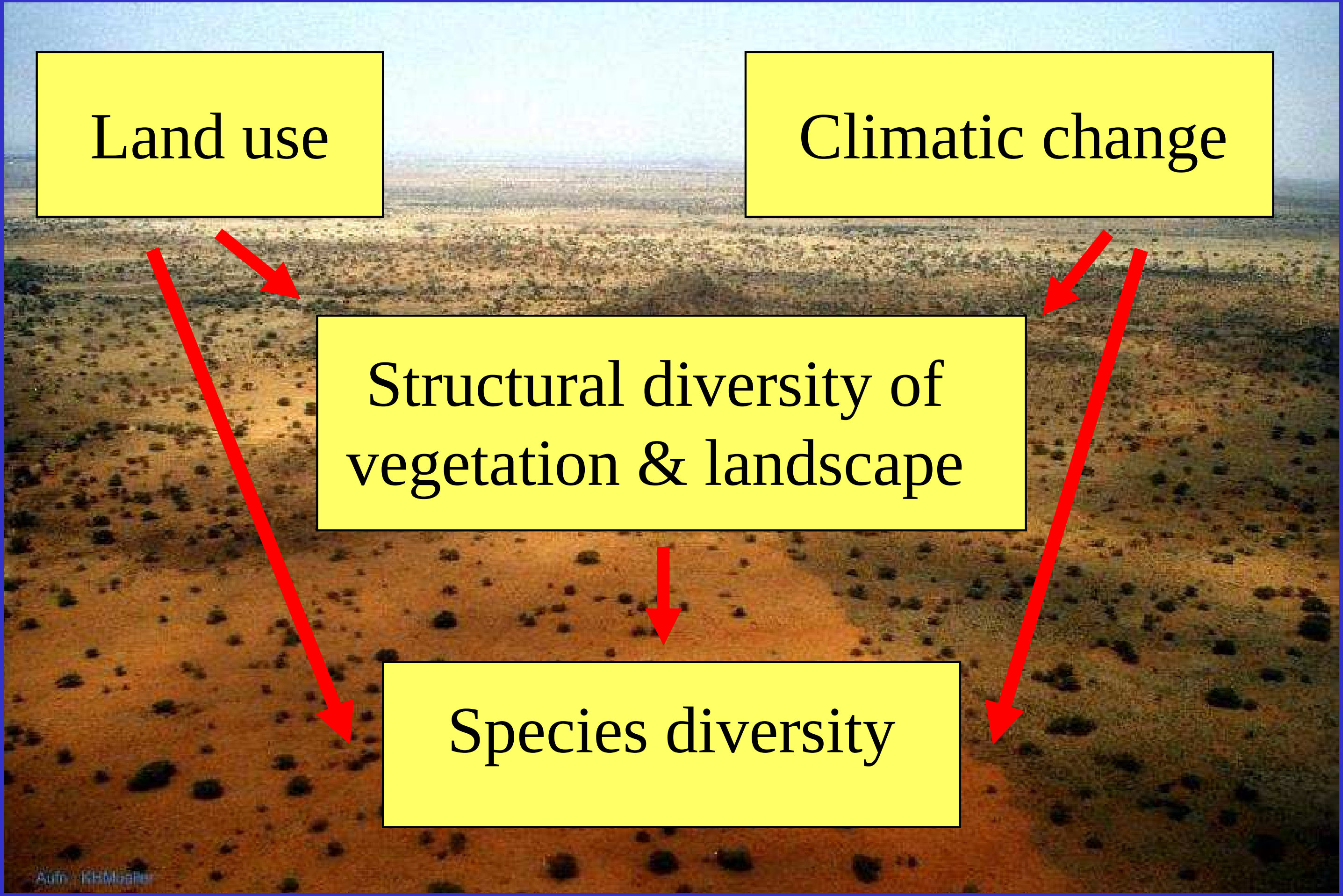
Milton,
Stellenbosch,
Bollig, Köln

Remote sensing, Geography

Müller,
Marburg

Modelling

Jeltsch, Potsdam



Land use

Climatic change

Structural diversity of vegetation & landscape

Species diversity

Better understanding of dynamic impact and interactions

↓

Implications for management strategies

Animal ecology

Dean,
Capetown;
Blaum, Bonn;

Brandl,Marburg

Plant ecology

Poschlod,
Regensburg;
van Rooyen,
Pretoria

Population genetics

Poschlod,
Regensburg;
Brandl,
Marburg

Key driver A:

climatic changes

- Decrease of precipitation
- Increase of extreme events

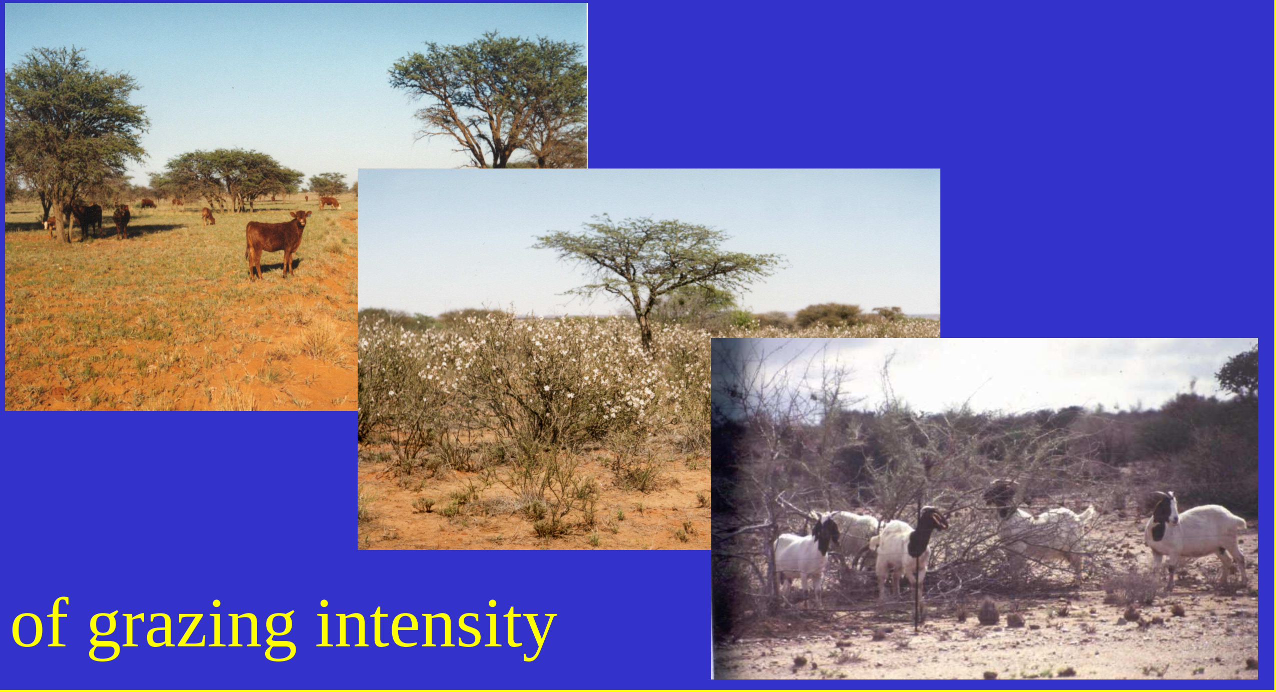
(e.g. Weltzin et al. 2003)

→ Systematic investigations

Key driver B:

overgrazing

High stocking rates lead to increase in woody vegetation cover = bush encroachment



→ systematic variation of grazing intensity

Key driver C: wood cutting - Consequences of tree felling for fire wood and charcoal production

Daai vure se dae nou getel

Wet oor kameeldoring toegepas

MARLEEN SMITH

VLEISBRAAIERS en kampvuur-

boom.

Hoewel dit al jare onwettig is om kameeldorings af te kap, het vroeëre wetgewing bepaal dat oortreders slegs vervolg kan word as hulle op heter daad betrap word terwyl hulle die boom kap. Dit het bewaarders se werk erg bemoeilik.

Nou kan enigeen wat dié gesogte hout vervoer, verkoop, koop of verwerk, ook vervolg word.

Me. Jennifer Kok, adjunk-direkteur: bosbouregulasies van die nasionale departement van waterwese en bosbou, sê die nodige regulasies behoort vroeg volgende jaar ingestel te wees.

Intussen kan oortreders reeds vervolg word kragtens 'n wetswysiging wat vroeër vanjaar in die Parlement aanvaar is.

Amptenare van die departement tree nou landwyd streng op om dié misdaad uit te roei. Dit is veral in Noord-Kaap 'n groot probleem, sê Kok.

Mnr. Malcolm Procter, beheerbosbouer van die departement in Bloemfontein, sê dit is nou baie makliker om oortreders vas te vat. Tot drie jaar tronkstraf kan opgelê word.

Hy sê mense laat dikwels na om indringerspesies soos die Suidwes-

doring vir brandhout te gebruik, terwyl skaars, inheemse kameeldoringhout by die tonne in rook op-

'n spesie wat stadig groei en is veral gewild omdat kole van die hout so lank brand.

Die grootste uitwissing van kameeldorings was met die diamantstormloop na Kimberley in die 1880's.

Toe is groot gebiede rondom dié destydse nedersetting, asook rondom Schmidtsdrift, Kathu en Vryburg, vir brandhout gestroop.

Die 45 cm breë dakbalke van Moffat se kerk in Kuruman is van kameeldoringhout – 'n aanduiding dat aansienlik groter en ouer kameeldorings as vandag tóé nog gegroei het. Terwyl uitwissing voortduur, is dit onwaarskynlik dat sulke groot kameeldorings ooit weer in Suid-Afrika gesien sal word.

Kameeldorings speel 'n waardevolle rol in ekostelsels en die behoud van biodiversiteit. Versamelvoëls bou hul neste in die bome omdat dit so stewig is en die horisontale takke onversperde toegang tot hul neste vergemaklik. Larwes van die topaas-skoenlapper voed op die bome.

Proctor herinner ook dat selfs die dooie, verrottende hout nie verwyder behoort te word nie, omdat dit 'n belangrike voedingsbron vir plante en insekte is.

Buite Burger 30 Nov 2001

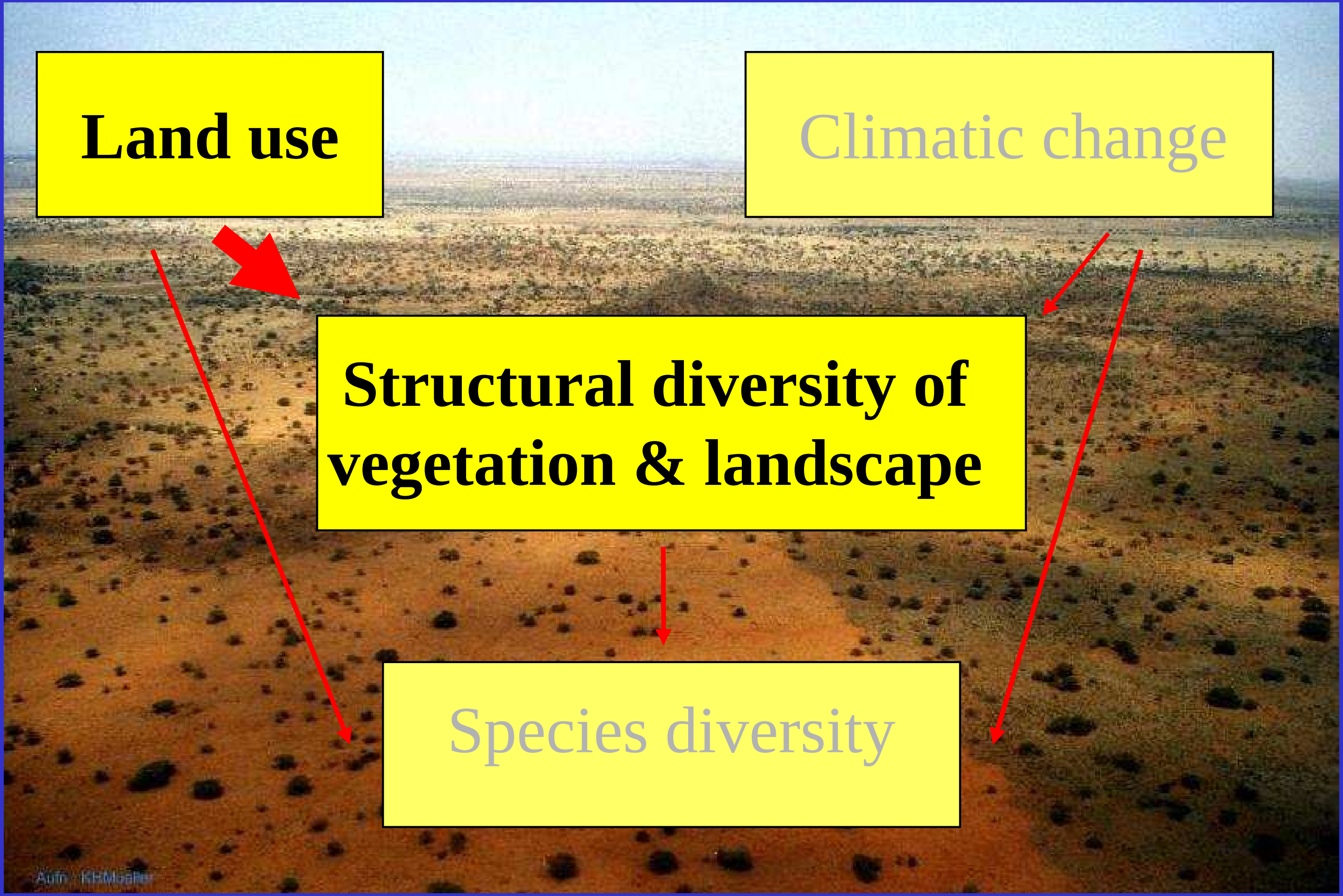
<u>Recent legislation prevents transport of Camelthorn wood.</u>

Fighting bush enroachment

Commercial harvesting

Calculations based on survey of the Nature Conservation group Stellenbosch (S. Milton et al.) : average rate of wood removal can be up to 0.5 % (non-commercial) and 5 % (commercial) of trees per year.

1. Land use – vegetation structures:



Land use

Climatic change

Structural diversity of vegetation & landscape

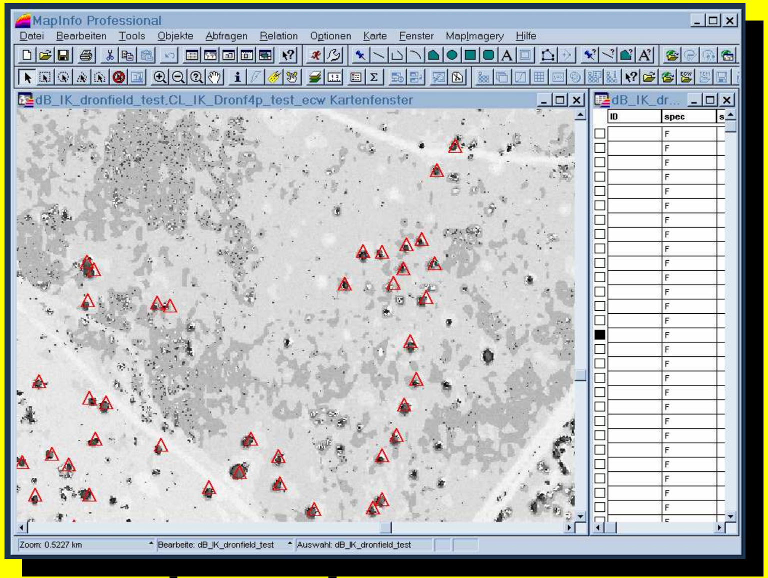
Species diversity

Twofold approach:

Remote sensing

Multitemporal aerial photos & satellite images

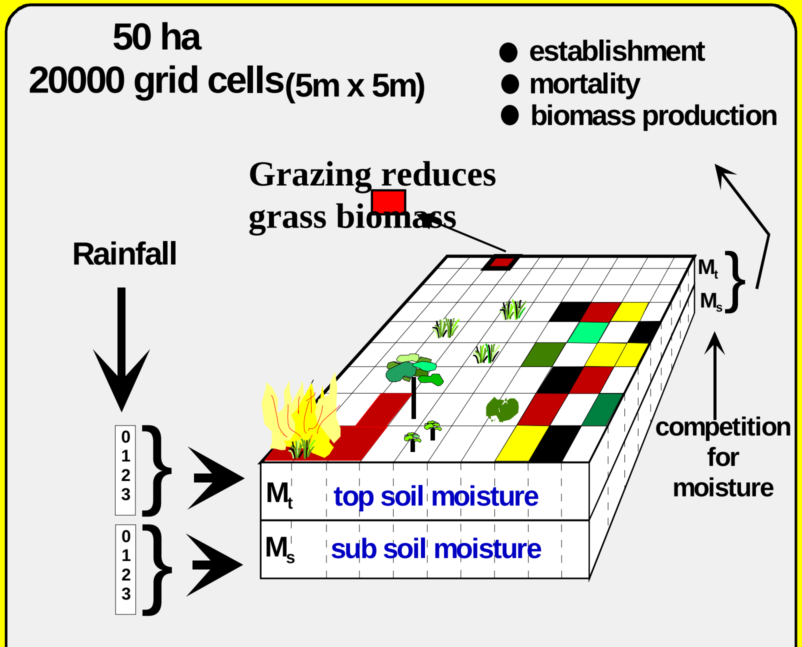
quantification of present and historical landscape structures



Moustakas et al. in press

Spatial modeling

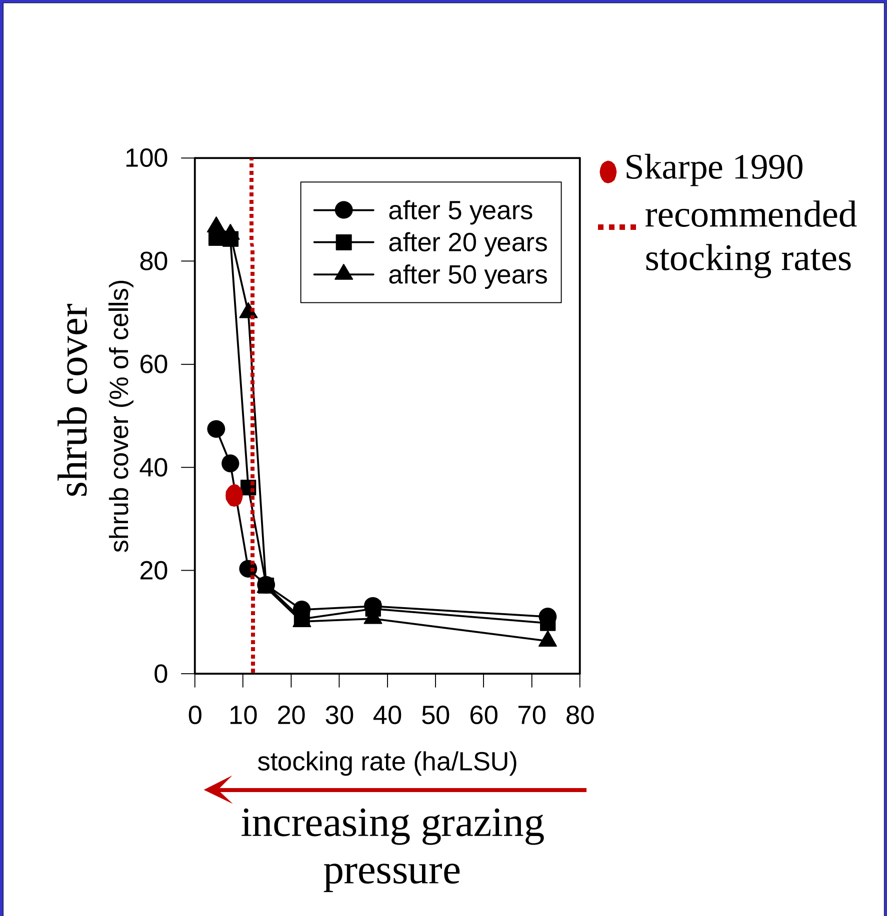
Dynamics of vegetation and habitat structures on landscape level



Jeltsch et al. 1996,97,98,99,2000)

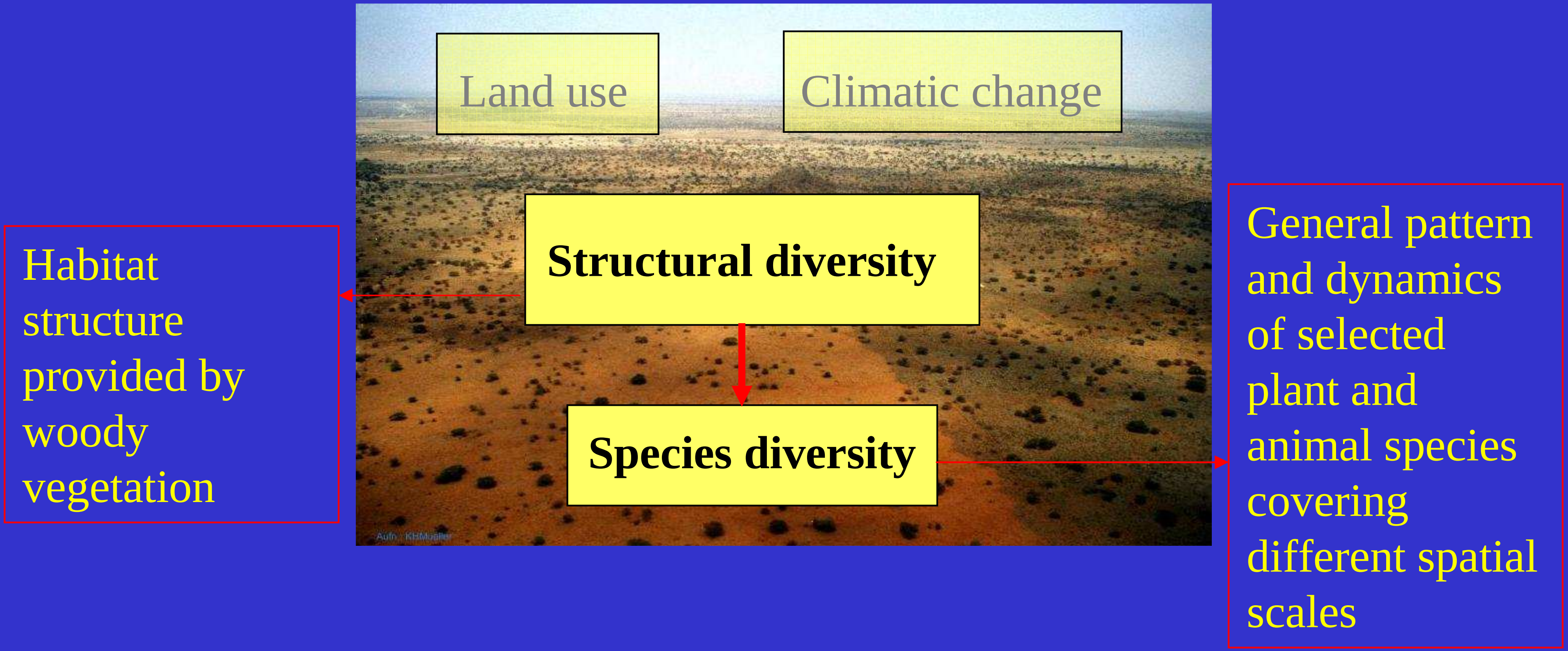
Changes in structural diversity

Sample model results: How much land use (= grazing pressure) is possible?



- Threshold of shrub encroachment vs. grazing pressure
- Recommended livestock densities underestimate risk of shrub encroachment at larger timescales (>10y)

2. Structural diversity → species diversity?



Land use

Climatic change

Structural diversity

Species diversity

Habitat structure provided by woody vegetation

General pattern and dynamics of selected plant and animal species covering different spatial scales

Aufn.: KHMueller

SPONSORED BY THE
Federal Ministry
of Education
and Research

Tawny eagle (*Aquila rapax*):

large spatial scale: territory radius 7 km, needs large solitary nesting trees, age < 16 years, slow population response, territories

Sociable weaver (*Philetairus socius*):

moderate to large spatial scales mean homerange radius <500m, needs large nesting trees > 70 y, age < 5, fast population response, non-territorial, metapopulation

Tree rat (*Thallomys nigricauda*)

Small scale: homerange radius 25 m, old tree + shrub, age 3 y, fast population response, females territorial

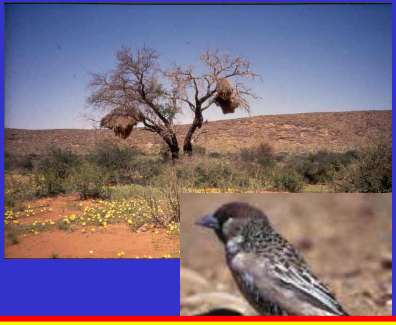
Raisin bush (*Grewia flava*)

Moderate scale, seed dispersal by birds and mammals, related to large trees, age high, slow recruitment (except cattle dispersal)

Tawny eagle (*Aquila rapax*):

large spatial scale: territory radius 7 km, needs large solitary nesting trees, age < 16 years, slow population response, territories

Sociable weaver (*Philetairus socius*):



moderate to large spatial scales mean homerange radius <500m, needs large nesting trees > 70 y, age < 5, fast population response, non-territorial, metapopulation

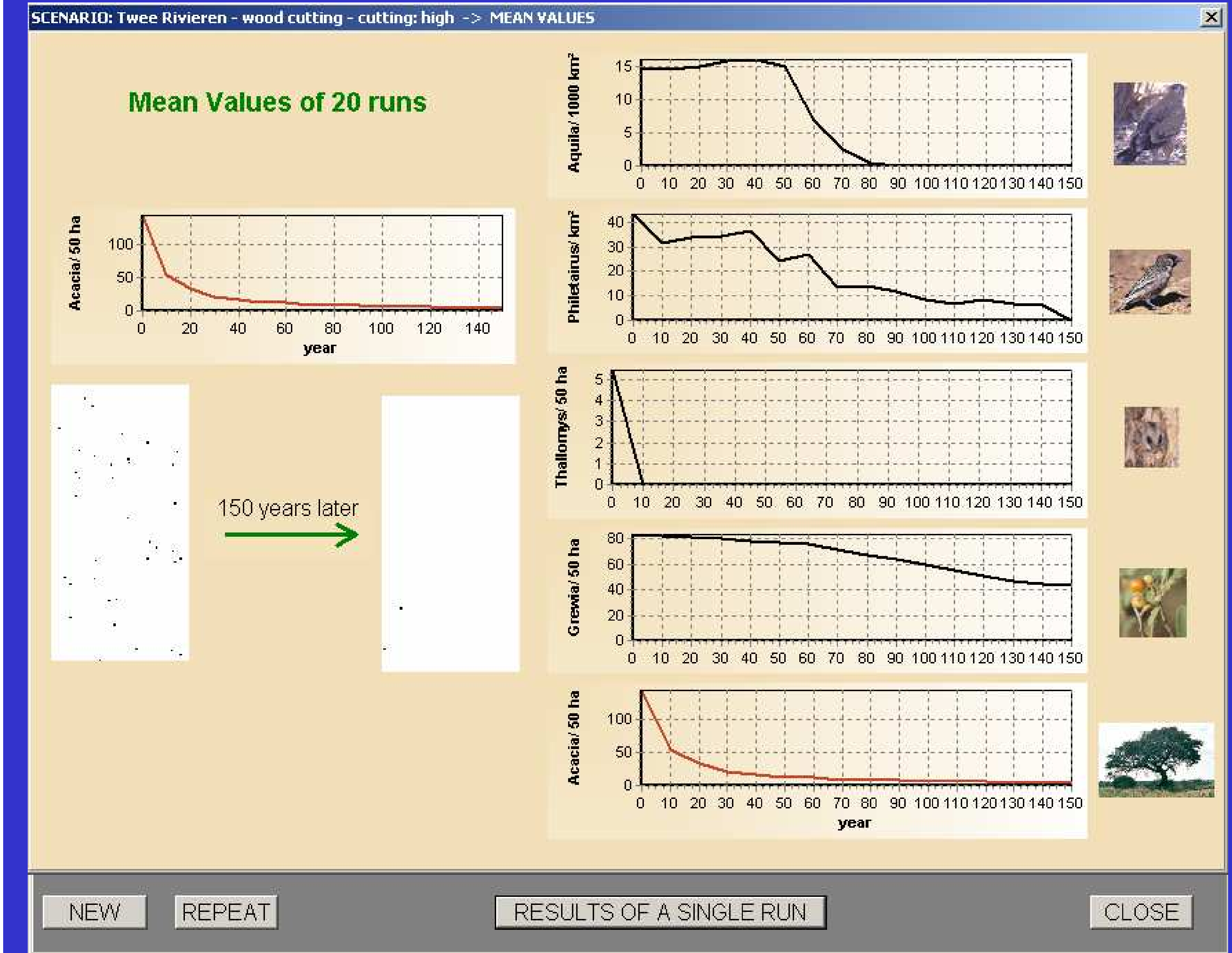
Spatially-explicit, stochastic population models (process models)

population response, females territorial

Raisin bush (*Grewia flava*)

Moderate scale, seed dispersal by birds and mammals, related to large trees, age high, slow recruitment (except cattle dispersal)

Sample result: ‚**commercial** tree felling‘ – southern Kalahari, low rainfall area, 200 mm



SCENARIO: Twee Rivieren - wood cutting - cutting: high -> MEAN VALUES

Mean Values of 20 runs

150 years later

extinction

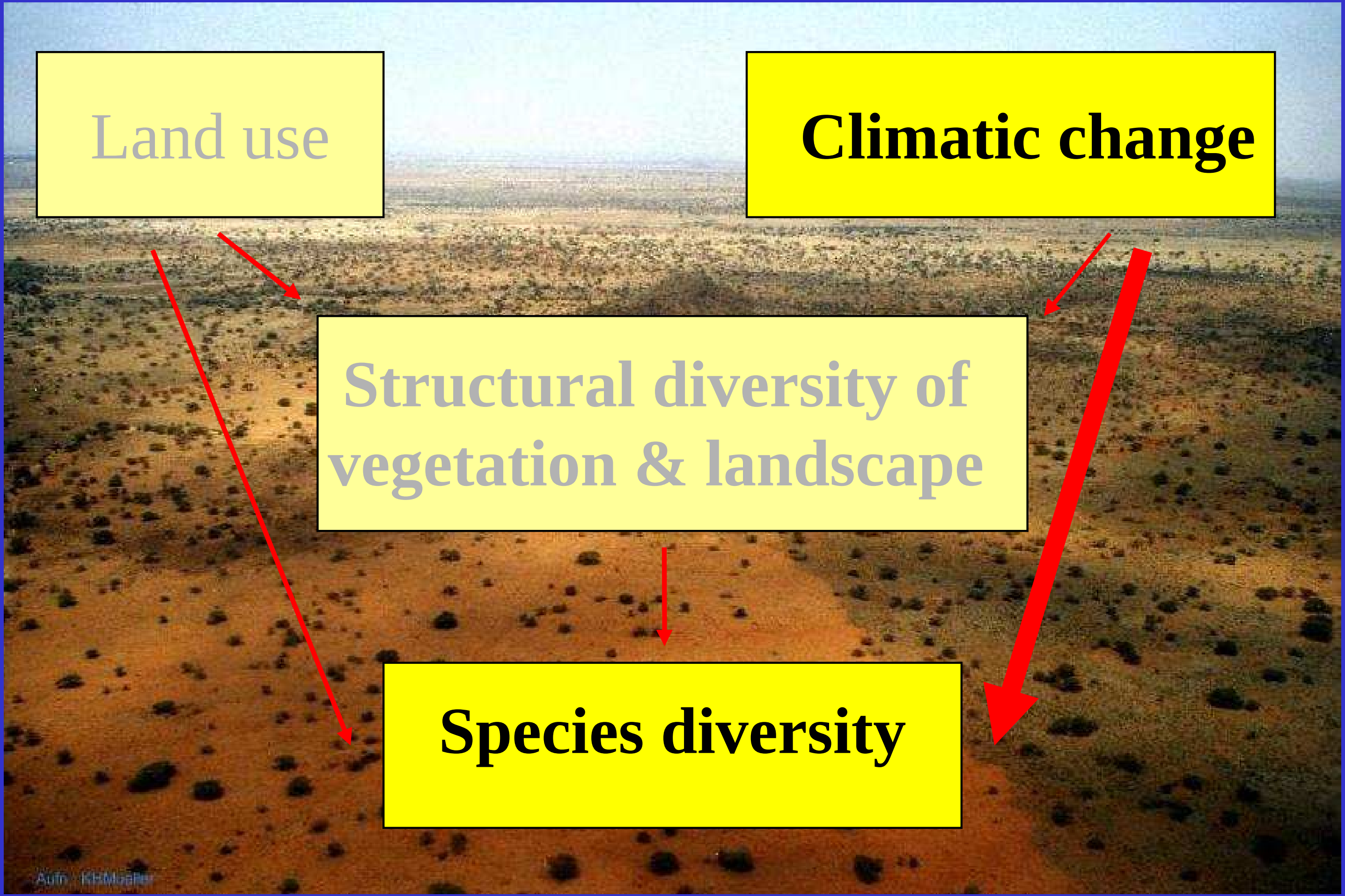
extinction

extinction

decrease

decrease

1. Climate change – species survival:



Land use

Climatic change

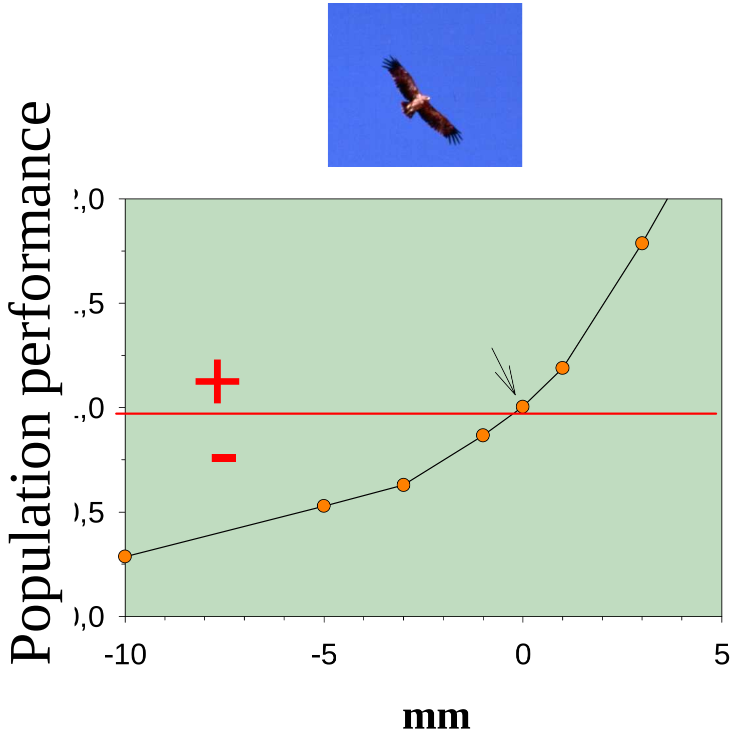
Structural diversity of vegetation & landscape

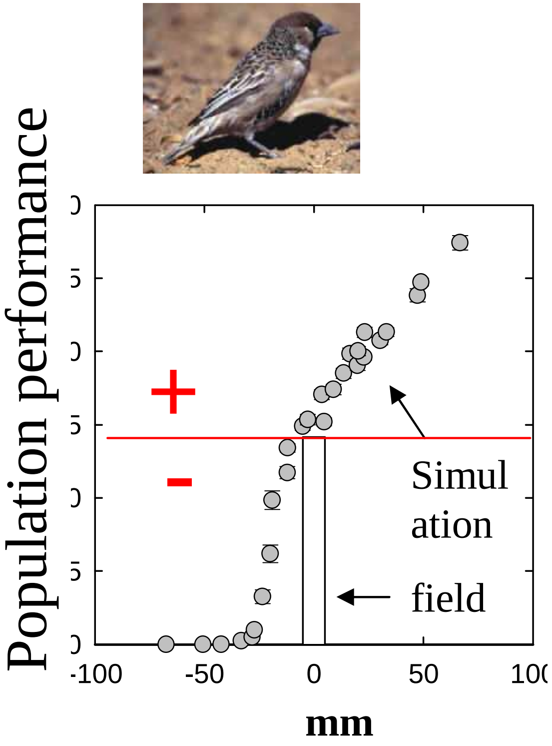
Species diversity

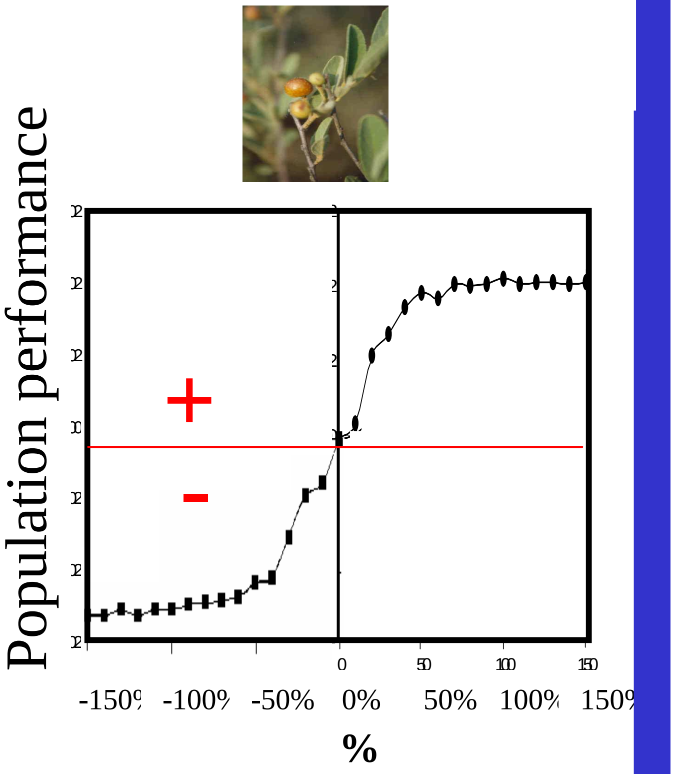
Aufn.: KHMüller

Climate changes → species diversity/ population survival

Population response to changes in mean annual precipitation







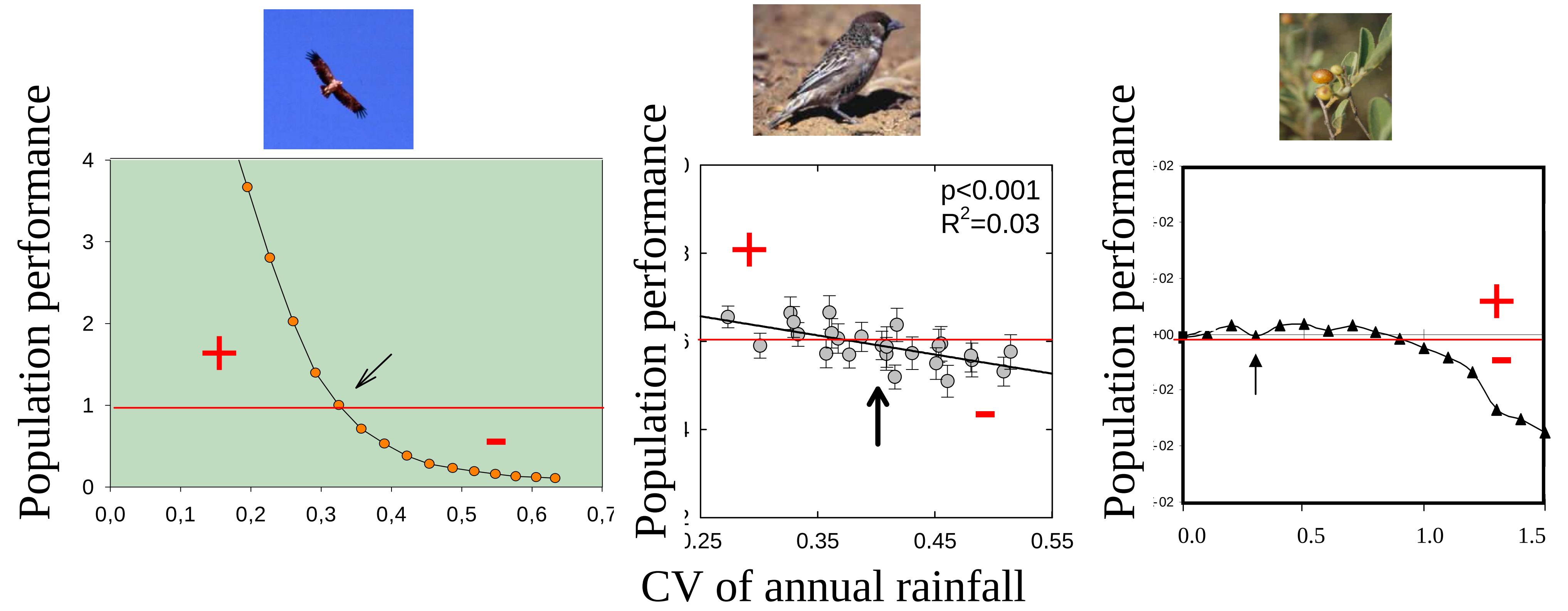
change in mean annual rainfall

Change in mean annual precipitation has strong, significant effects on all species

Sensitive processes: reproduction, mortality

Climate changes → species diversity/ population survival

Population response to changes in variability of precipitation (CV) - unchanged mean value!



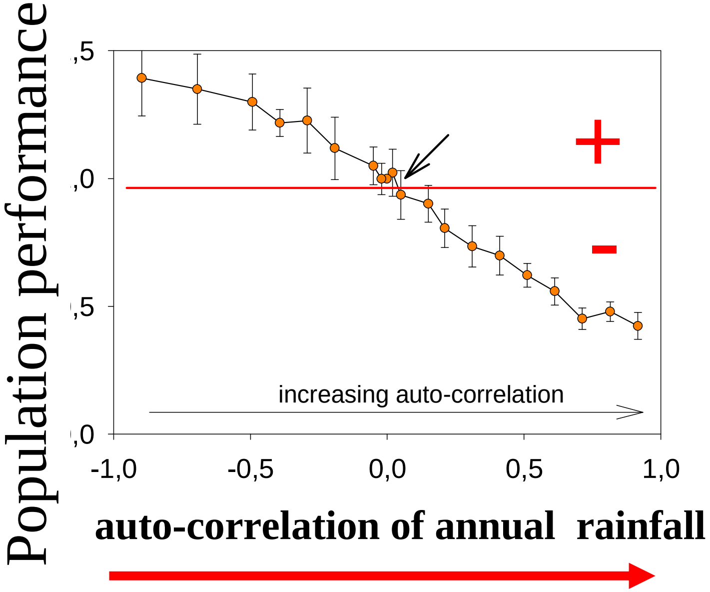
Changes in rainfall variability can have strong effects on some species

Sensitive process for tawny eagle: capacity (territories) limits positive effects of more good years but full effect of more negative years

Climate changes → species diversity/ population survival

Population response to changes in temporal auto-correlation of precipitation (cycles, e.g. caused by El Nino)

Unchanged mean value
and constant CV

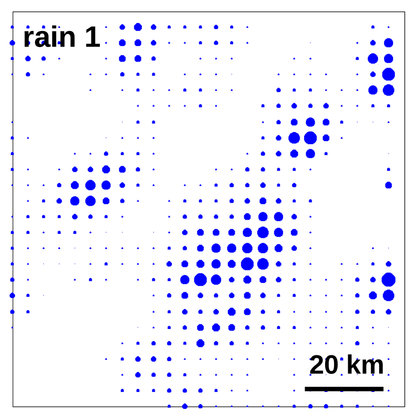


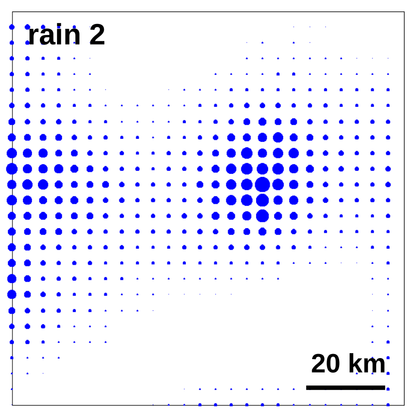
Changes in temporal correlation of precipitation (e.g. cycles) can have moderate effect on some species

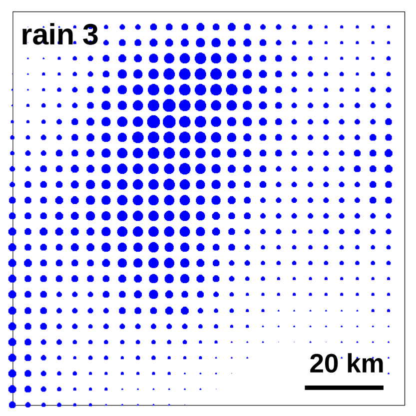
Sensitive process: same as rainfall variability

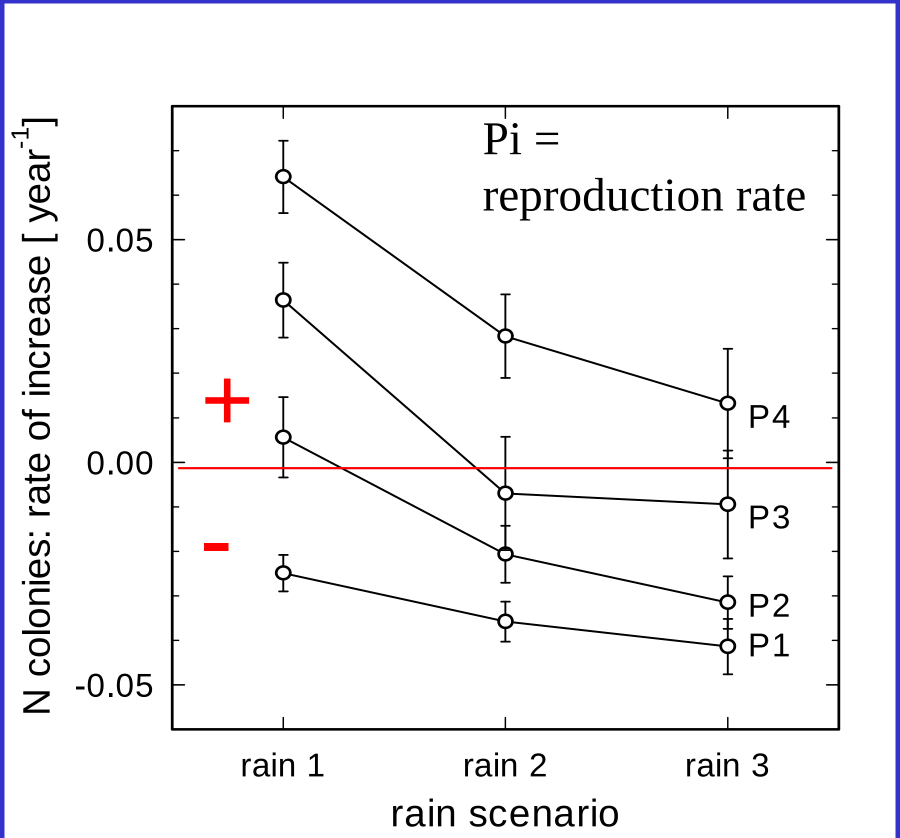
Climate changes → species diversity/ population survival

Increasing spatial autocorrelation of rain has a negative effect on spatially-structured populations (e.g. metapopulation of sociable weavers)









Sensitive process: Correlated extinction of neighbouring sub-populations in drought periods

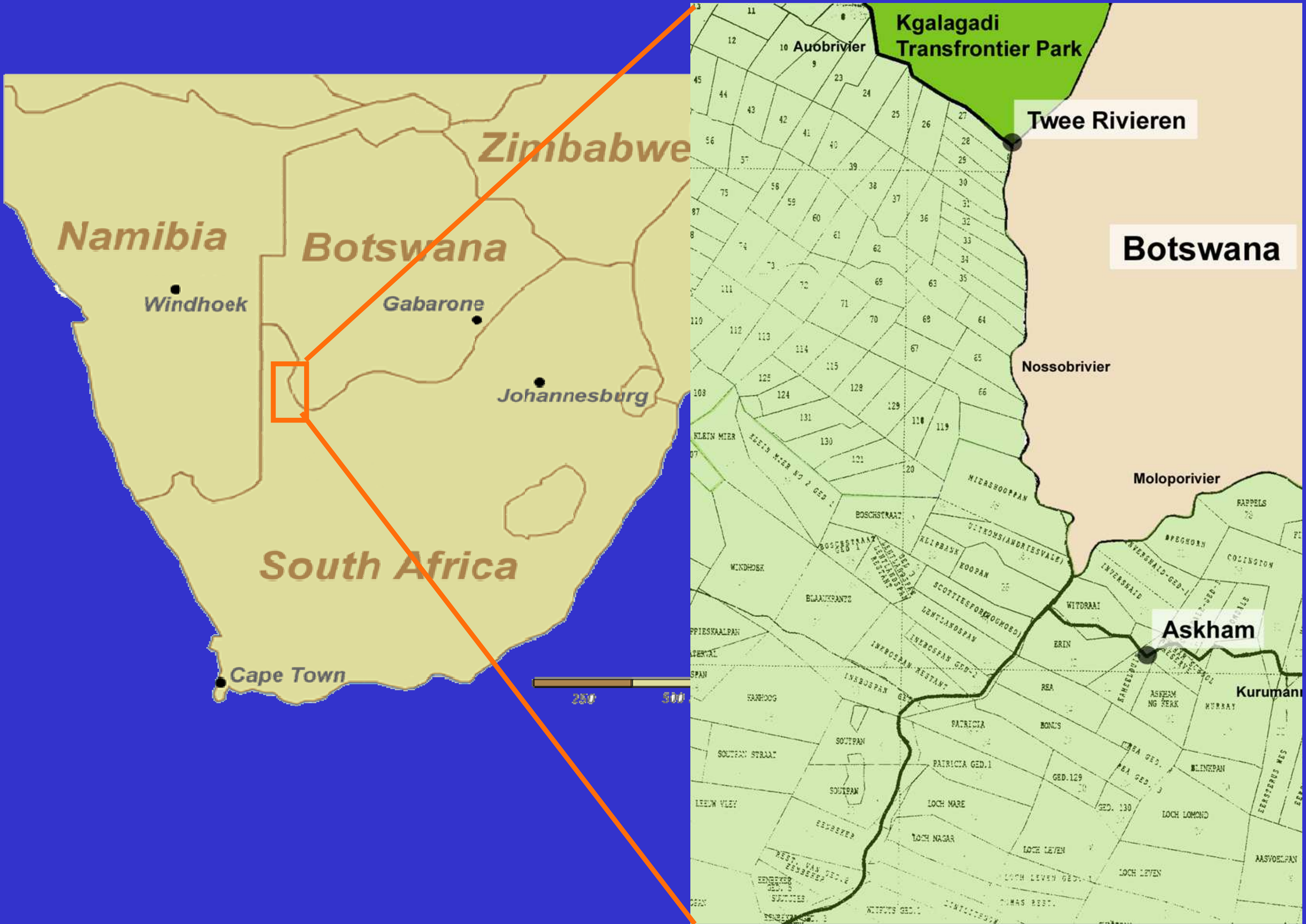
Climate changes → species diversity/ population survival

Species response to climatic changes:

- Changes in mean → strong effect
- Changes in variability → moderate to strong effect for some species
- Changes in temporal or spatial correlation → moderate to strong effect for some species

Process knowledge on population level is necessary to predict response to changes

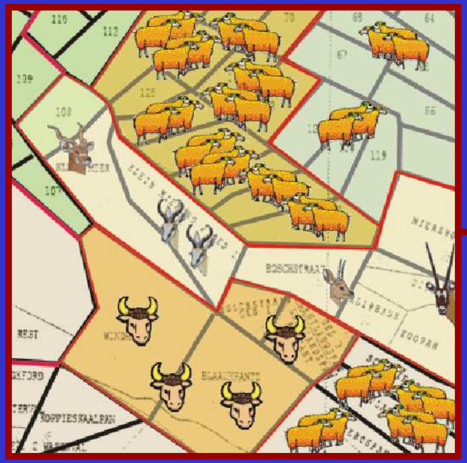
Outlook1 : Scaling up



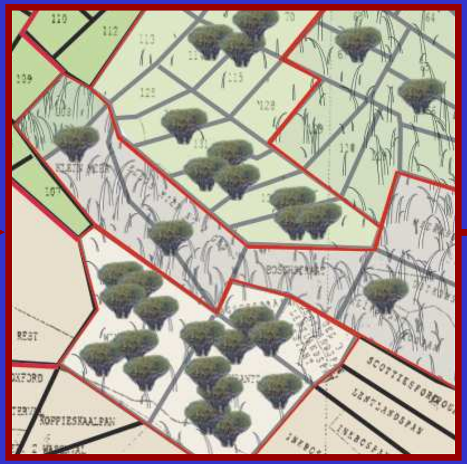
Background

Aim

Understanding the processes on large spatial scales



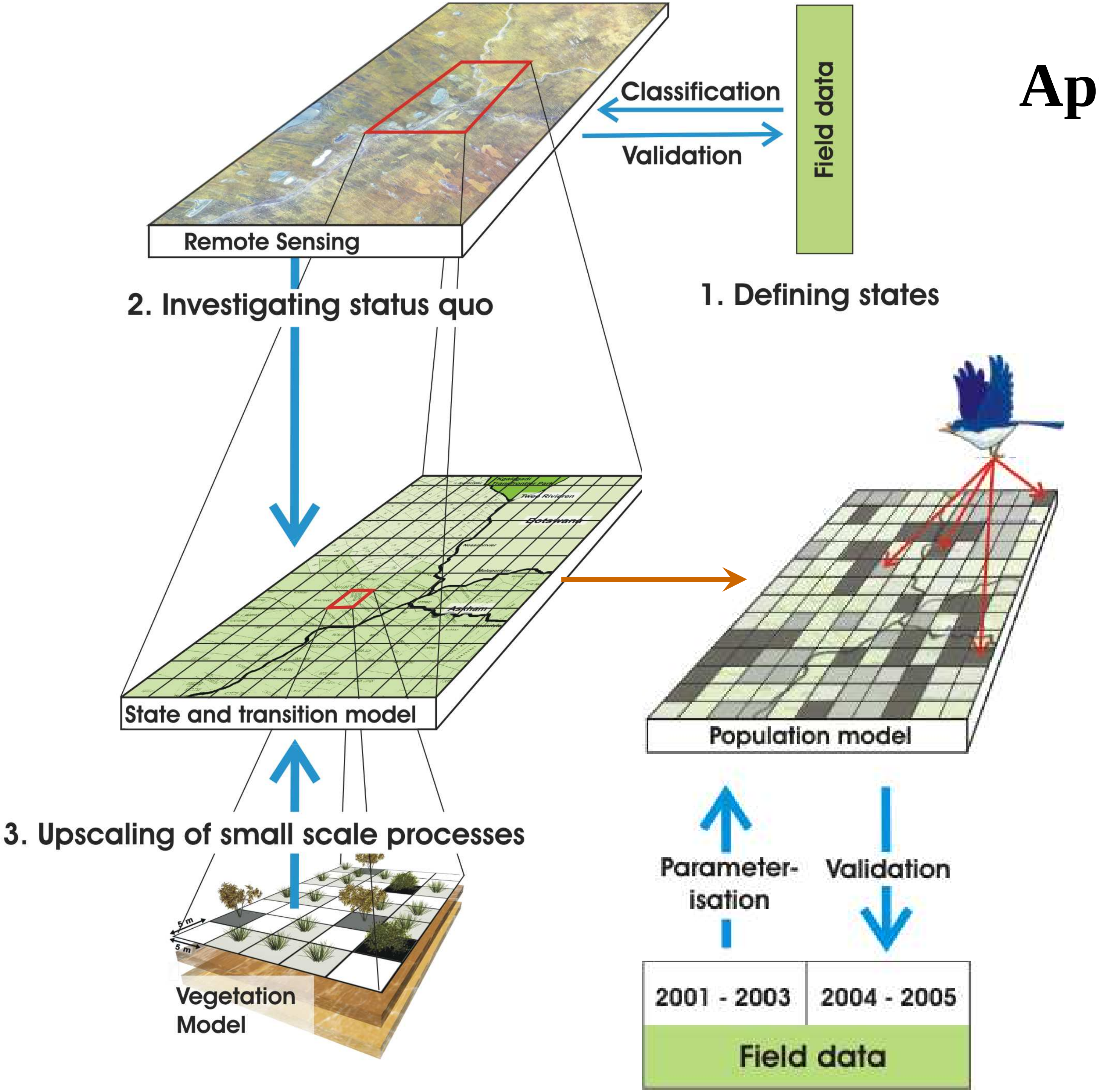
Mosaic of
land use types



Mosaic of vegetation
states and structures

Population dynamics
of species

Approach



Remote Sensing

Classification

Validation

Field data

1. Defining states

2. Investigating status quo

State and transition model

Population model

3. Upscaling of small scale processes

Vegetation Model

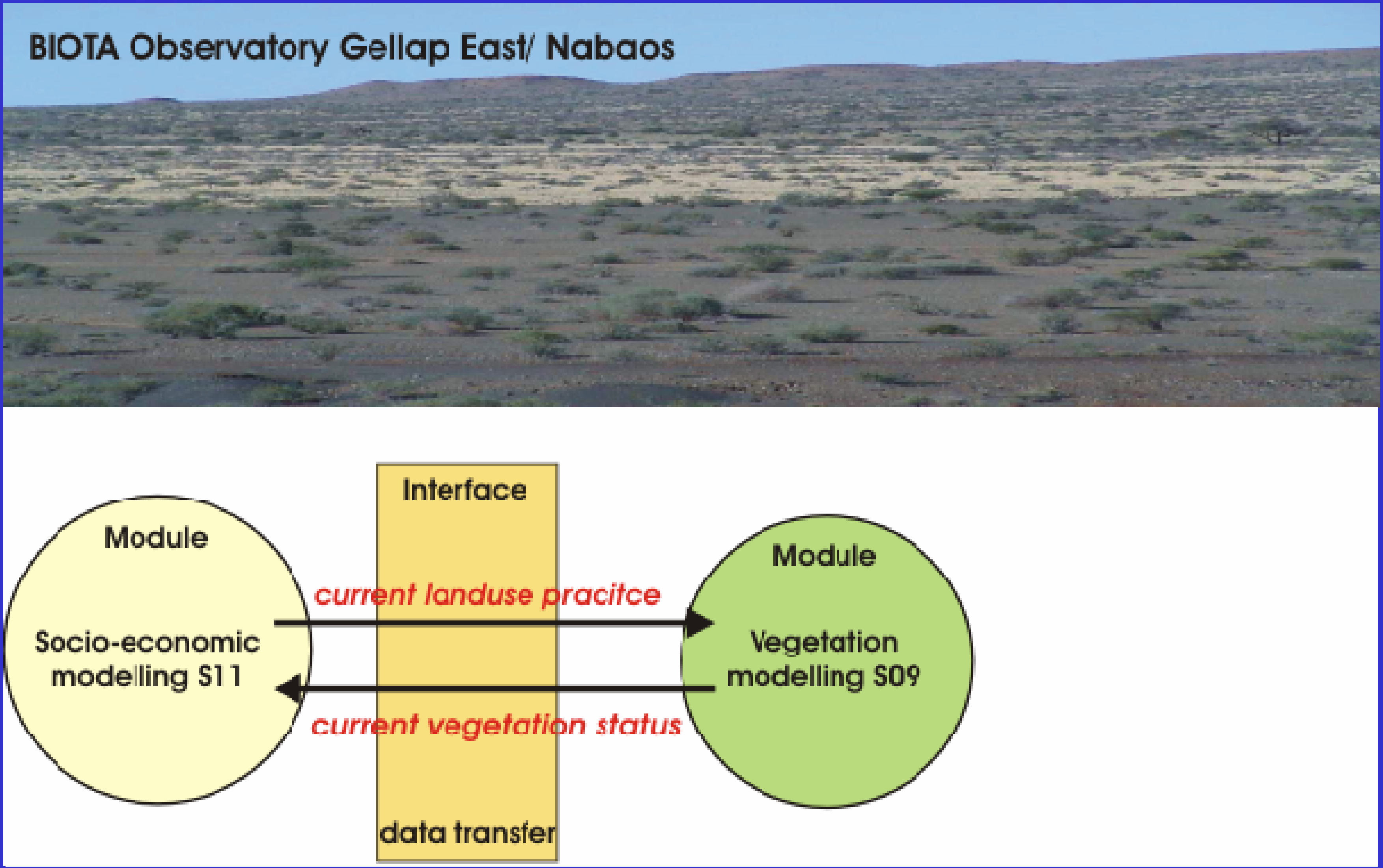
Parameter-isation

Validation

2001 - 2003	2004 - 2005

Field data

Outlook 2:
Bio – economic modelling



Conclusions

- Ecological systems are **very** complex
- Analyzing ecological systems requires a multidisciplinary approach
- Models are an important tool in analyzing ecological systems
- Mostly models need to be spatially explicit and stochastic

Thanks for your attention