Land sparing or sharing or something in between?

Multi-objective land use optimization based on scenario analysis

Michael Strauch, Anna Cord, Anne Jungandreas, Andrea Kaim, Martin Volk
Multiple demands on agricultural landscapes

**Production**
- Food
- Bioenergy

**Water**
- Water quality
- Groundwater recharge
- Environmental flow
- Hydropower

**Recreation**
- Active
- Passive

**Biodiversity**
- Species richness
- Functional diversity

**Trade-offs**
- Best case
- Worst case
Land use intensity and landscape configuration

Land sparing vs. Land sharing

Land sharing/sparing debate, e.g.:  
Phalan et al. / Science 333 (2015), 1289-1291  
Von Wehrden et al. / Landscape Ecol 29 (2014), 941–948
Workflow

Scenario development (stakeholder discussion)

Common storylines for land sharing, land sparing, and business as usual

Spatial targeting of management options

Multi-objective optimization

**SWAT**
crop yield, runoff, water quality

**Biodiversity model**
bird species distribution

**Result**
Scenario impacts on ESS and biodiversity

Comparison
Where can we be more efficient with measures?

**CoMOLA**
Linking **SWAT**, biodiversity model with NSGAII

**Result**
Landscape potential (trade-off curves)
Workflow

Scenario development (stakeholder discussion)

Common storylines for land sharing, land sparing, and business as usual

Procedure and examples in the TALE Learning Environment
   tale.environmentalgeography.nl

Crop yield, runoff, water quality

Biodiversity model
   bird species distribution

Result
   Scenario impacts on ESS and biodiversity

Result
   Landscape potential (trade-off curves)

Comparison
   Where can we be more efficient with measures?
Study area

Lossa River Basin (141 km²)

Land cover:
- Barren
- Deciduous forest
- Coniferous forest
- Mixed forest
- Cropland
- Horticulture
- Extensive grassland
- Intensive grassland
- Build-up area
- Transportation
- Water

Germany
Study area: Lossa River Basin
Scenarios

Spatially explicit land cover changes

Current

Business as usual

Land sharing

Land sparing

Land cover change (%)
- No change
- Deciduous forest (+0.61)
- Extensive grassland (+8.5)
- Built-up area (+1.12)
- Cropland (-1.73)
- Intensive grassland (-6.5)

Land cover change (%)
- No change
- Deciduous forest (+0.24)
- Cropland (+1.51)
- Horticulture (+0.05)
- Extensive grassland (-0.36)
- Intensive grassland (-1.44)
### General land cover /land use changes

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>B. as usual</th>
<th>Land sharing</th>
<th>Land sparing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop rotations</td>
<td>According to crop statistics</td>
<td>Slightly less diverse</td>
<td>Slightly more diverse</td>
<td>Strongly less diverse</td>
</tr>
<tr>
<td>Org. farming (%)</td>
<td>4</td>
<td>5</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>Fertilizer (kg N/P)</td>
<td>112/31</td>
<td>105/36</td>
<td>81/30</td>
<td>122/39</td>
</tr>
<tr>
<td>Tillage (% conserv.)</td>
<td>60</td>
<td>70</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>Linear elements (e.g. hedges)</td>
<td>According to land use map</td>
<td>No change</td>
<td>Increase</td>
<td>Decrease</td>
</tr>
</tbody>
</table>
1) Soil and Water Assessment Tool (SWAT)

- **Process-based** integrated watershed model
- Calibrated and validated for *streamflow*, *total loads of nitrogen*, *phosphorus* and *suspended solids* as well as *crop yields*
- Basin-wide *agricultural gross margin* (in €) calculated from simulated crop yields and crop-specific costs and market prices

2) Bird habitat model

- Nine **Random Forest models**, one for each of the nine observed bird species breeding in agricultural sites of the Lossa Basin
- Taking into account **up to 21 predictor variables** (climate, soil, land use, linear elements and distance parameters)
- Output: *suitable habitat for each of nine species*
Multi-objective optimization beyond scenario analysis

Is it more effective to spatially target the different land use / management options at HRU level?

Biodiversity

Production

Pareto or Production Possibility Frontier

Land sharing

Business as usual

Land sparing

Status quo
Optimization

Max breeding habitat

Min NO3 load

Mid-range solution

Land sharing

Max Lowflow

Business as usual

Land sparing

Max production

Status quo
Optimization

Max production

Max breeding habitat

Mid-range solution

Max lowflow

Min NO3 load

Land cover/use according to:
- Status quo
- Business as usual
- Land sharing
- Land sparing
Analysis of optimization results

Why did those land cover/management patterns emerge?
=> spatial factor analysis

Which solutions are preferred?
=> involve stakeholders

Which specific management recommendations can be derived?
=> visualize allocation of single measures
Suggestion according to mid-range solution:

Δ change of line area compared to status quo [% of HRU area]
Conclusions

• **Scenario analysis** revealed trade-offs among agricultural production and biodiversity (and water quality)

• **Multi-objective optimization** of land use at HRU level as a way to minimize the trade-offs (non-dominated solutions outperform stakeholder-based scenarios for land sharing and land sparing)

• **Challenging**: In-depth-analysis and **interpretation** of results as well as illustration of model **uncertainties**

• **Food for discussion** with stakeholders and decision-makers on „where to put things“ in landscapes to optimally provide multiple ecosystem services and biodiversity at the same time
**Annex**

**SWAT input data**

- **DEM**
- **Stream gauges**
- **Point sources**
- **Reservoirs**

**Subbasins**

- **Land cover map**
- **Soil map**
- **Slope map**

**HRUs**

- **Plant parameters**
- **Management settings**
- **Soil parameters**

**Simulation**

- **Hydrological and other reference data**

**Calibration/Evaluation**

- **Discharge**
- **Nutrient loads**
- **Crop yield**

**Scenario data**

**Scenario runs**

- **Weather data**

- **Precipitation**
- **Temperature (min,max)**
- **Wind**
- **Solar radiation**
- **Humidity**
Annex

**SWAT model performance**

- **Streamflow**
- **Water quality**
- **Crop yield**

**Crop**
- Spring barley
- Silage corn
- Sugar beet
- Triticale
- Winter barley
- Winter rapeseed
- Winter rye
- Winter wheat

**KGE Performance**
- Erlin: KGE=0.77
- Golzern: KGE=0.86
- Bad Düben: KGE=0.76

**Lower part Mulde Basin**

**Nordsachsen**

**Simulated yields [dry t/ha/a]**

**Observed yields [dry t/ha/a]**

**Crop yield comparison**
- TN: KGE=0.71, KGE=0.68, KGE=0.51
- TP: KGE=0.19, KGE=0.33, KGE=0.23
- TSS: KGE=0.1, KGE=0.32, KGE=0.15

**Streams and Discharge**

**Graphs**
- Streamflow graphs for Erlin, Golzern, and Bad Düben
- Water quality graphs for TN, TP, and TSS
**Scenario Design: Land use/cover**

SQ = Status quo
LBA = Business as usual
LSP = Land Sparing
LSH = Land Sharing

**LULC**
- Built-up area
- Forest
- Pasture, int.
- Pasture, ext.
- Cropland
- Other

**Conversion rules**

SQ
LBA
LSP
LSH

Annex
Scenario Design: Agricultural management

Percentage on cropland

Type of farming
- Conventional
- Organic

Type of tillage
- Conventional
- Minimum

Type of crop
- Alfalfa
- Corn
- Farmland grass
- Spring barley
- Sugar beet
- Winter barley
- Winter rape
- Winter rye
- Winter wheat

Percentage
Scenario Design: Agricultural management

Annex

- **Cropland**
  - SQ: 156 kg/ha/yr
  - LBA: 145 kg/ha/yr
  - LSP: 168 kg/ha/yr
  - LSH: 104 kg/ha/yr

- **Pasture, int.**
  - SQ: 140 kg/ha/yr
  - LBA: 130 kg/ha/yr
  - LSP: 140 kg/ha/yr

- **Pasture, ext.**
  - SQ: 90 kg/ha/yr
  - LBA: 85 kg/ha/yr
  - LSP: 60 kg/ha/yr

Type of fertilizer:
- N
- P
Source: ATKIS-DLM

Polylines representing tree rows and hedges

2.5m buffer overlaid with HRU map

Habitat quality effect in Biodiv models

Filter effect in SWAT

HRU filter strip width (m) = \text{linE area (m}^2\text{)} / \text{HRU perimeter (m)}
Scenario Design: Linear elements (linE)

Min for LSH: Upper quartile of SQ
Max for LSP: Median of SQ
Biodiversity on the example of birds

Breeding birds dataset from Saxon State Agency of Environment, Agriculture and Geology (LfULG)

13 species with sufficient number of observations for modeling of breeding habitat within the lower part of the Mulde River basin
**Predictor variables**

**Land use**  
(within a radius of 250 m)  
- Urban  
- Transportation  
- Cropland  
- Pasture (total, extensive, intensive)  
- Forest (total, deciduous, coniferous, mixed)  
- Horticulture  
- Wetlands  
- Water  
- Barren

**Linear elements**  
- Share on HRU area  
- Share on HRU perimeter  
- Forest edges

**Distance parameters**  
Distance to:  
- Next stream  
- Next road

**Soil**  
- Available water capacity  
- Bulk density  
- Carbon content  
- Satur. hydraulic conductivity

**Climate**  
- Temperature  
- Temperature ranges  
- Precipitation
Annex

Presence and absence

**Presence data points** available for each species:

500 m buffer around each data point to avoid overlay of predictor variables

Data points for other species outside the buffer **considered as Pseudo-absence**:
Variable selection

-> Reduction of the 26 variables using:

- pseudo-$R^2$
- RMSE

Selected variables

(for each species ten repetitions)
Variable selection

**Land use** (within a radius of 250 m)
- Urban
- Transportation
- Cropland
- Pasture (total, extensive, intensive)
- Forest (total, deciduous, coniferous, mixed)
- Horticulture
- Wetlands (species-specific need)
- Water
- Barren

**Linear elements**
- Share on HRU area
- Share on HRU perimeter
- Forest edges

**Distance parameters**
Distance to:
- Next stream
- Next road

**Soil**
- Available water capacity
- Bulk density
- Carbon content
- Saturated hydraulic conductivity

**Climate**
- Temperature
- Temperature ranges
- Precipitation
Modeling with decision trees (Random Forest)

Random generation of a **decision tree** based on the data:

Repeated 500x = „Forest“

(for each species ten repetitions)
Prediction of breeding habitat

Land use scenario

Prediction using all ten models per species

Presence/absence is a majority decision
Annex

Model performance

pseudo-R²

<table>
<thead>
<tr>
<th>Species</th>
<th>Pseudo-R²</th>
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<tbody>
<tr>
<td>Turteltaube</td>
<td>100%</td>
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<tr>
<td>Bekassine</td>
<td>80.7%</td>
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<tr>
<td>Schilfrohrsänger</td>
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<tr>
<td>Steinschmaetzer</td>
<td>40%</td>
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<td>Schleiereule</td>
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<tr>
<td>Rauchschwalbe</td>
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</tr>
<tr>
<td>Kiebitz</td>
<td>0%</td>
</tr>
<tr>
<td>Heidelerche</td>
<td>0%</td>
</tr>
<tr>
<td>Haubenlerche</td>
<td>0%</td>
</tr>
<tr>
<td>Gartenrotschwanz</td>
<td>0%</td>
</tr>
<tr>
<td>Eisvogel</td>
<td>0%</td>
</tr>
<tr>
<td>Dohle</td>
<td>0%</td>
</tr>
<tr>
<td>Braunkehichen</td>
<td>0%</td>
</tr>
</tbody>
</table>

Mean: 80.7%

RMSE

(data range: 0-1)

<table>
<thead>
<tr>
<th>Species</th>
<th>RMSE (Mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turteltaube</td>
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<tr>
<td>Bekassine</td>
<td>0.10</td>
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<td>Schilfrohrsänger</td>
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</tr>
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</table>

Mean: 0.17
CoMOLA

Constrained Multi-objective Optimization of Land use Allocation

NSGA-II and GA algorithms from *inspyred* Python package enhanced for land use optimization (maps, models, constraints)

**Constraint handling methods:**

- Constraint-controlled genome generation & repair mutation (CG-CM)
- Constraint Tournament Selection (CTS)

The tool

1. Encode original land use map as first individual of initial population
2. Constraint-controlled genome generation (CG) to fill up initial population
3. Run model(s), quantify objectives
4. Non-dominated sorting
5. Termination criteria reached?
   - Yes
   - No
6. Tournament selection, cross-over, mutation
7. Constraints satisfied?
   - Yes
   - No
8. Constraint-controlled repair mutation (CM)
9. Stop
Annex

1. Prepare input land use map and (optionally) constraints

2. Provide models
   - cropyield.R
   - habitatheterogen.R
   - speciesrichness.R

3. Configure optimization
   - Paths/Filenames/
   - Optimization algorithm/
   - Population size/
   - Max. number of generations/
   - Mutation rate/
   - Crossover rate/
   - Extreme seeds/
   - Variator/Selector/
   - Constraint handling/

4. Run optimization
   - Encode original land use map as first individual of initial population
   - Constraint-controlled genome generation (CG) to fill up initial population
   - Run model(s), quantify objectives
     - Non-dominated sorting
       - Yes
         - Termination criteria reached?
           - Yes
           - No
         - Tournament selection, cross-over, mutation
       - No
     - Constraints satisfied?
       - Yes
       - Constraint-controlled repair mutation (CM)
       - No

5. Visualize and analyze results

https://github.com/michstrau/CoMOLA