Optimization Basics and CAST Optimization Plan

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JANUARY 19, 2021

MICHIGAN STATE UNIVERSITY

Agenda

- Introduction to Michigan State University (MSU) Team
- Principles of Optimization Methods
- Proposed CAST System Optimization

Introduction to MSU Team

- Kalyanmoy Deb, Professor
  - Optimization algorithms, Multi-objective optimization, Modeling, Machine learning, Multi-criterion Decision support
- Pouyan Nejadhashemi, Professor
  - Computational Ecohydrology, Watershed modeling, Decision Support System
- Gregory Toscano, Post-doc Researcher
  - Evolutionary optimization, Decision Making, Multi-objective Optimization
- J. Sebastian Hernandez-Suarez, Doctoral Student
  - Watershed modeling and optimization
- Julian Blank, Doctoral Student
  - Evolutionary optimization, Surrogate-assisted optimization

Optimization Methods to be used in the Project

- Optimization methods: Point versus Population approaches
- Hybrid and Customized optimization principle
  - Population-based methods and structured point-based methods
- Multi-objective optimization
  - Evolutionary multi-objective optimization
  - Pattern discovery and use in optimization

Optimization Methods: Point and Population Based

Point-Based

Population-Based

Best for Convex and simplistic problems

Best for local search

Nonlinear Programming

$$\nabla f(x) - \sum_{j=1}^{J} u_j \nabla g_j(x) - \sum_{k=1}^{K} v_k \nabla h_k(x) = 0$$

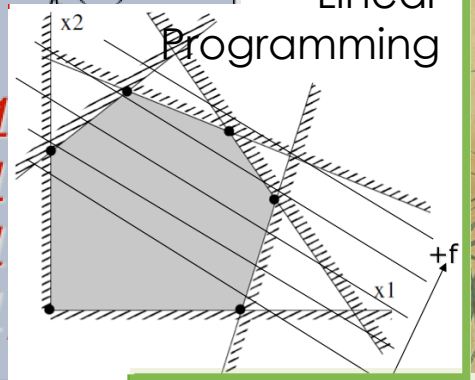
$g_j(\boldsymbol{x}) \geq 0 \quad j = 1$

$h_k(\boldsymbol{x}) = 0 \quad k = 1$

$u_j g_j(\boldsymbol{x}) = 0 \quad j = 1$

$u_j \geq 0 \quad j = 1$

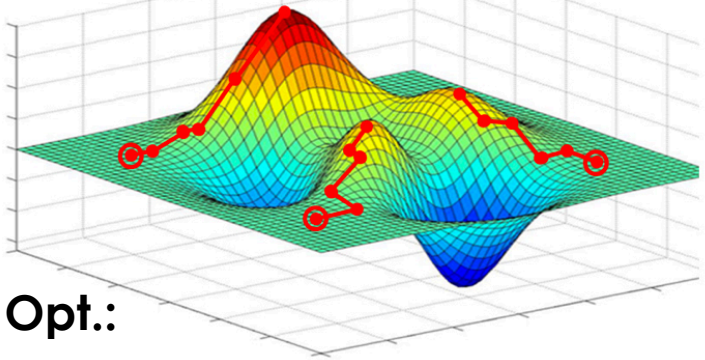
Linear Programming



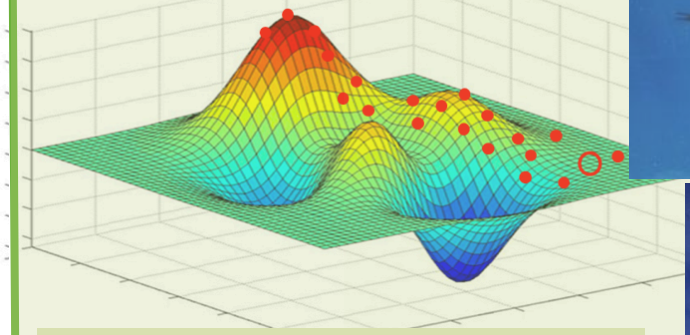
Best for non-convex and complex problems

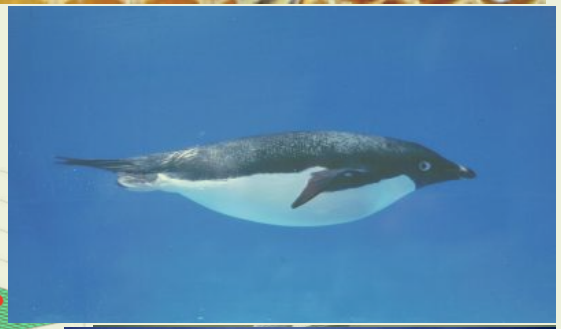
Best for global search

Math. optimization



Evolutionary optimization





Single-obj Opt.:

Search for a point which minimizes an objective function satisfying constraints

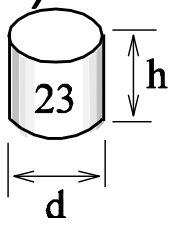
Other Meta-heuristics based methods

Goldberg, D. E. (1989). *Genetic algorithms for search, optimization, and machine Learning*, Reading, MA: Addison-Wesley.

Evolutionary Optimization: A Population-based Approach – Binary-coded Genetic Algorithm (BGA)

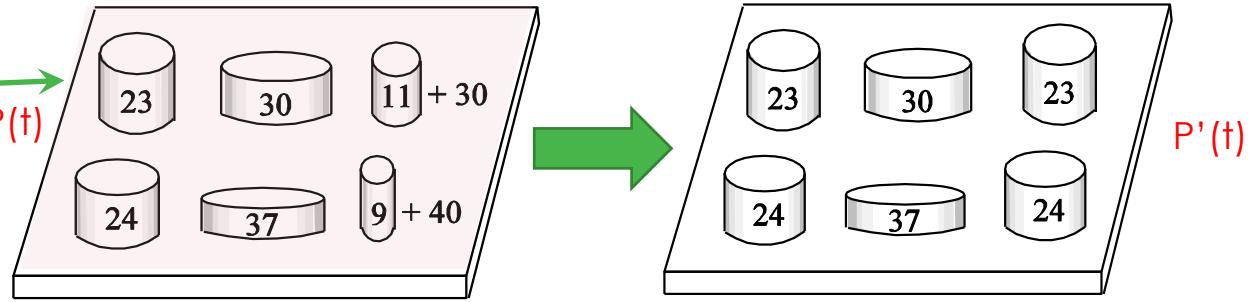
begin
Solution Representation
t := 0;
Initialization P(t);
Evaluation P(t);
while not Termination
do
P'(t) := Selection (P(t));
P"(t) := Variation (P'(t));
Evaluation P"(t);
P(t+1):= Survivor (P(t),P"(t));
t := t+1;
od
end

Can Design:

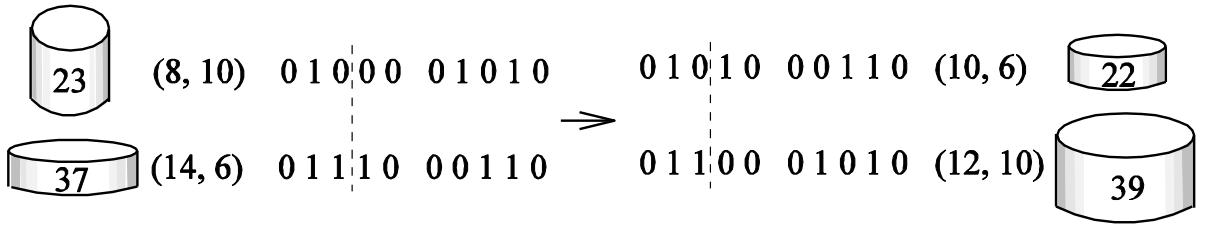


(d, h) = (8, 10) cm
(Chromosome) = 0 1 0 0 0 0 1 0 1 0

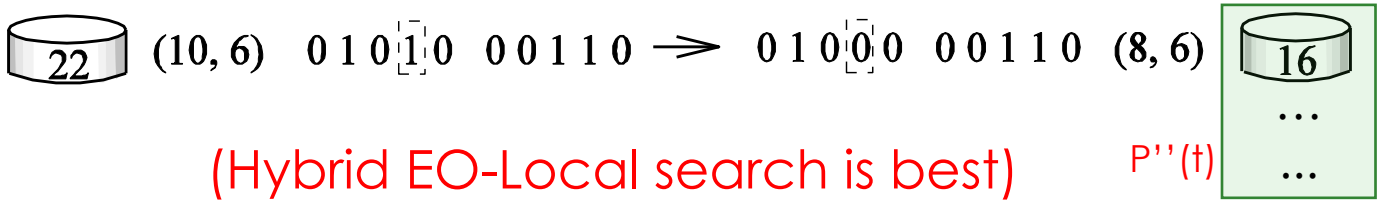
Selection:

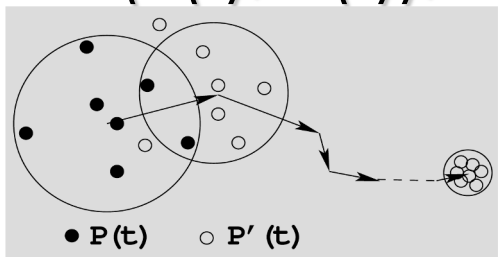


Recombination:



Mutation:





(Hybrid EO-Local search is best)

A Fact About Optimization Methods

No-Free Lunch (NFL) theorem:

- Wolpert and Macready (1997)
- Algorithms A1 and A2
- All possible problems **F**
- Performances P1 and P2 using A1 and A2 for a fixed number of evaluations
- P1 = P2
- NFL breaks down for a narrow class of problems or algorithms
- Suggests to develop and use a **Customized Optimization** method, rather than a generic method

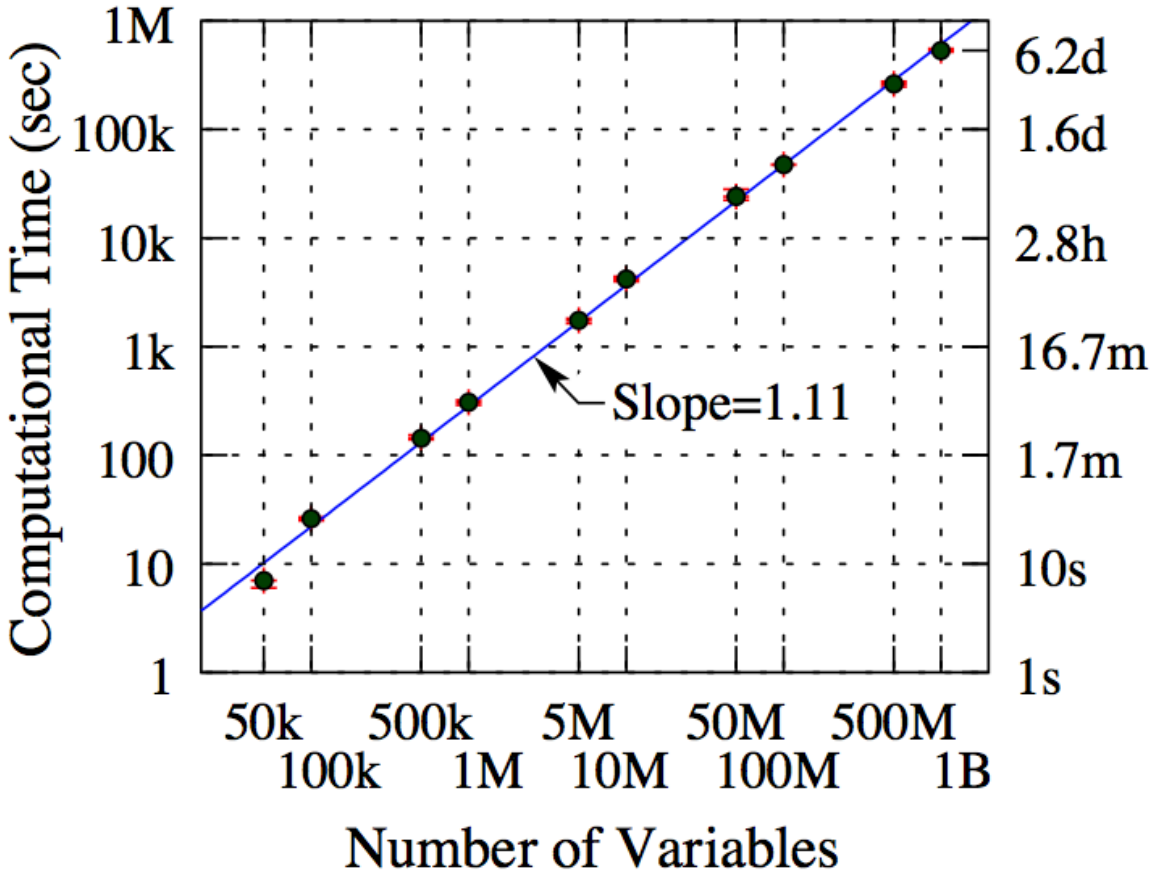
D. H. Wolpert and W. G. Macready. No free lunch theorems for optimization. *IEEE Transactions on Evolutionary Computation, 1*(1):67–82, 1997.

Some Past Applied Optimization Studies by the PIs

- A polynomial-time algorithm for a **Billion-variable** integer linear program
- Customized algorithms for **Rolling mill sequencing**, **Manufacturing process, Airline crew scheduling**, etc.
- Popular **multi-objective algorithms** (NSGA-II, NSGA-III)
- An astronomically large-sized **Land Use Management** problem with 14 objectives and involving human decision-makers
- A **Gasoline Engine design** for 6 objectives with 145 variables and 146 constraints
- A **Water Jacket design** for better heat transfer requiring 2 days of evaluation per solution involving 500+ processors

A Case Study: Customized Optimization

- Casting scheduling with large dimensions
  - 50k variables to start
- CPLEX cannot solve ≥2,000 variables
- Custom recombination and mutation operators
- Custom GA solves one **Billion-variable** problem in polynomial time

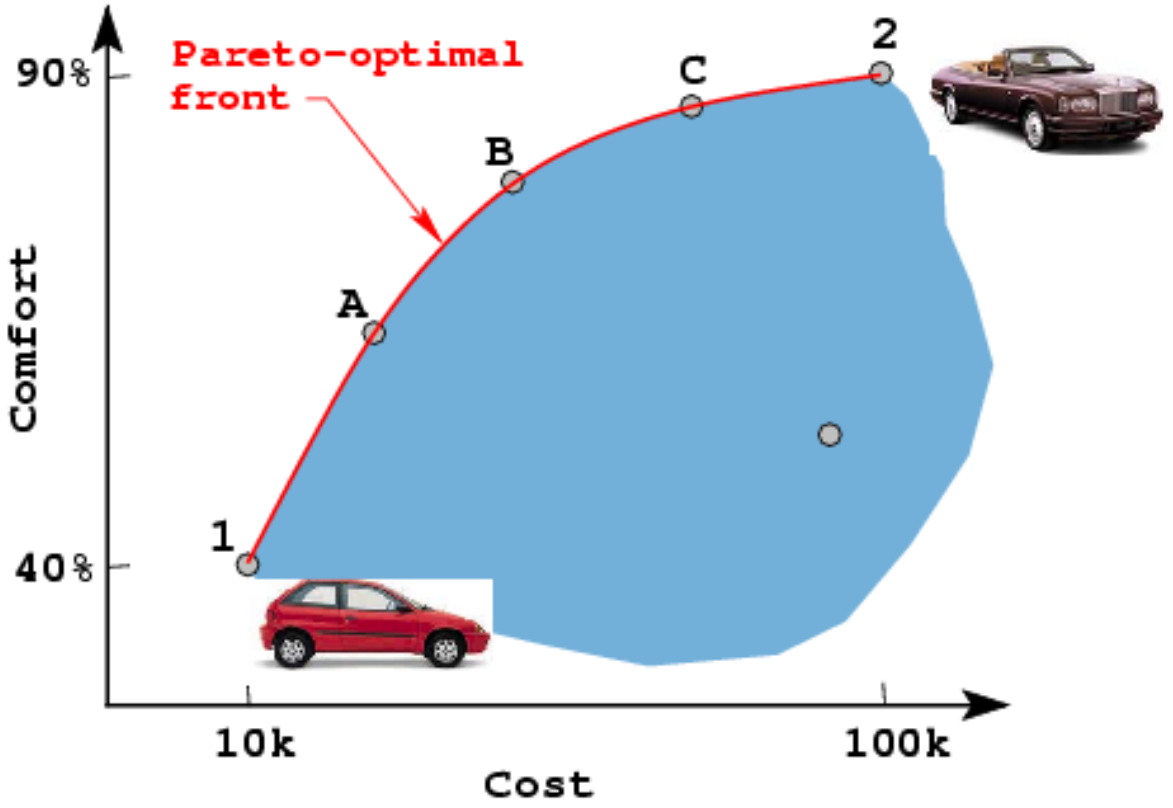


Deb, K. and Myburgh, C. (2017). A Population-Based Fast Algorithm for a Billion-Dimensional Resource Allocation Problem with Integer Variables. *European Journal of Operational Research, 261*(2), 460–474.

Deb, K. (2001). *Multi-objective optimization using evolutionary algorithms*. Chichester, London: Wiley,

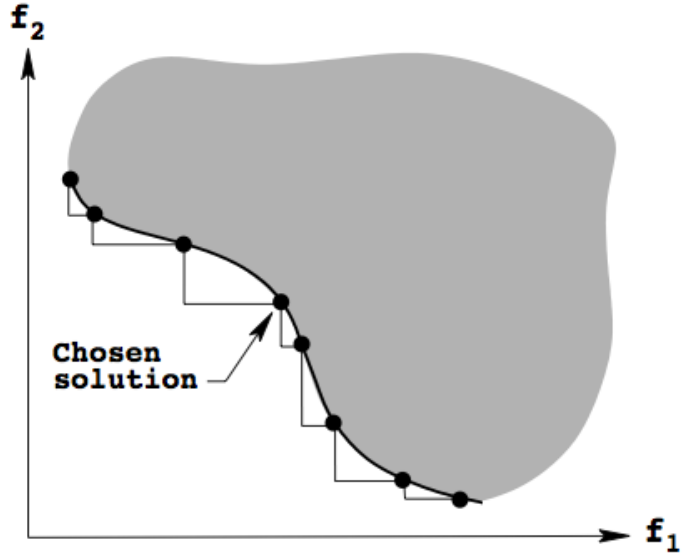
Multi-Objective Optimization

- Results in a set of Pareto-optimal solutions
- EO's population can store multiple solutions
  - Implicit parallelism helps
- NSGA-II, NSGA-III (commercialized) solve 2-15 objectives with constraints
- **Custom Evol. MO** (EMO) for applied problems

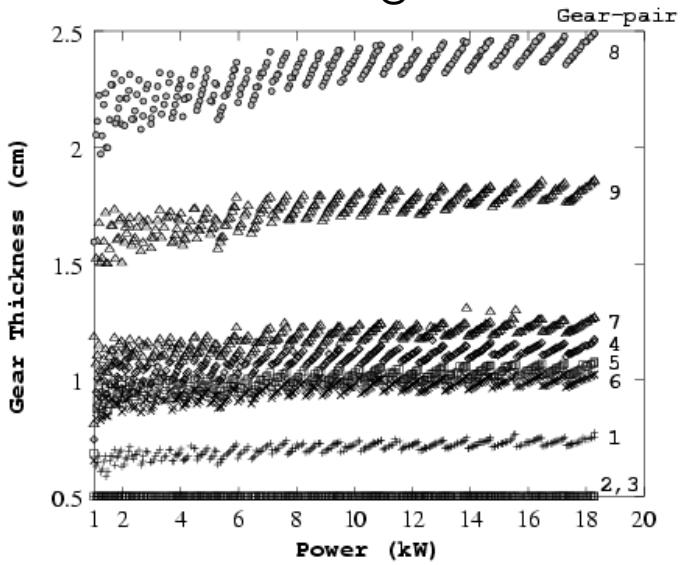


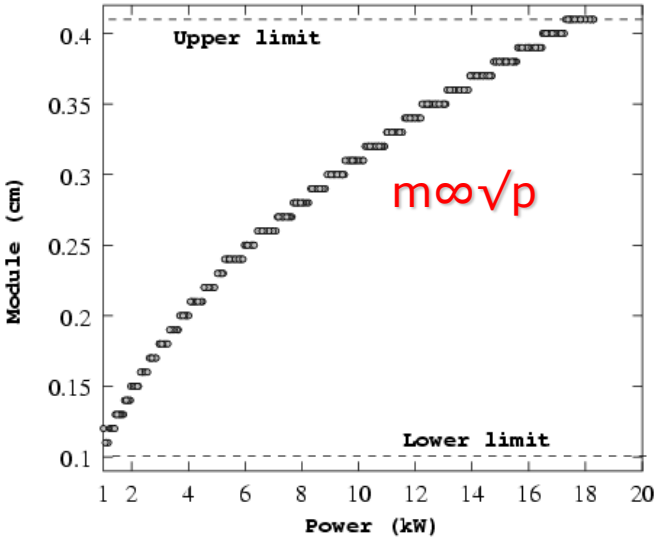
EMO and Decision-Making

- **Decision-making**: A systematic algorithmic approach
  - Trade-off analysis to choose a preferred solution
  - Interactive EMO-MCDM methods exist
- "**Innovization**"
  - Finding patterns in Pareto-optimal solution for knowledge discovery using AI/ML methods



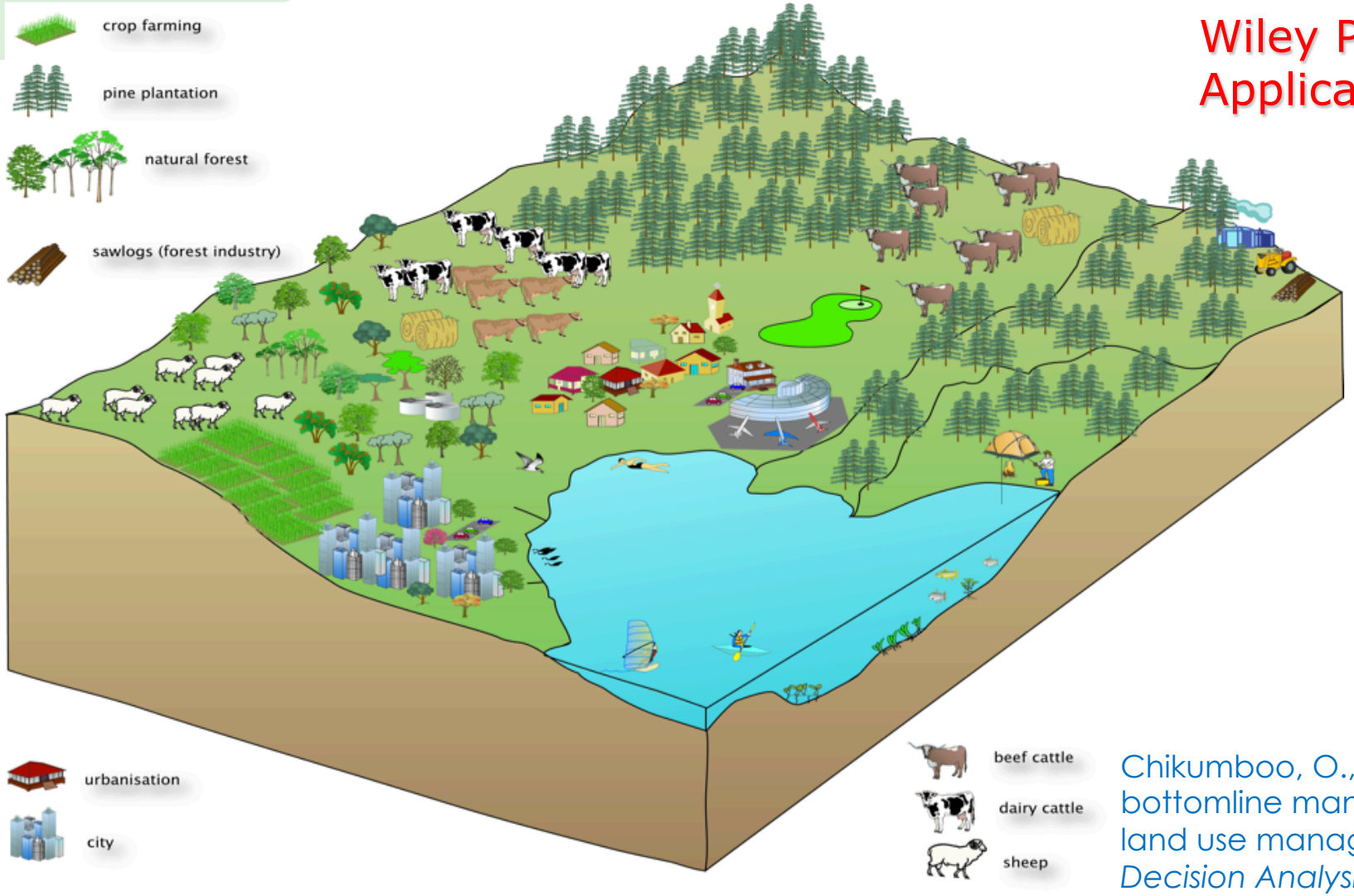
A Gear-box design:





Deb, K. and Srinivasan, A. (2006). *Innovization*: Innovating design principles through optimization. *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO2006)*, New York: The Association of Computing Machinery (ACM), (pp. 1629–1636)

Case Study: New Zealand Land Use Management

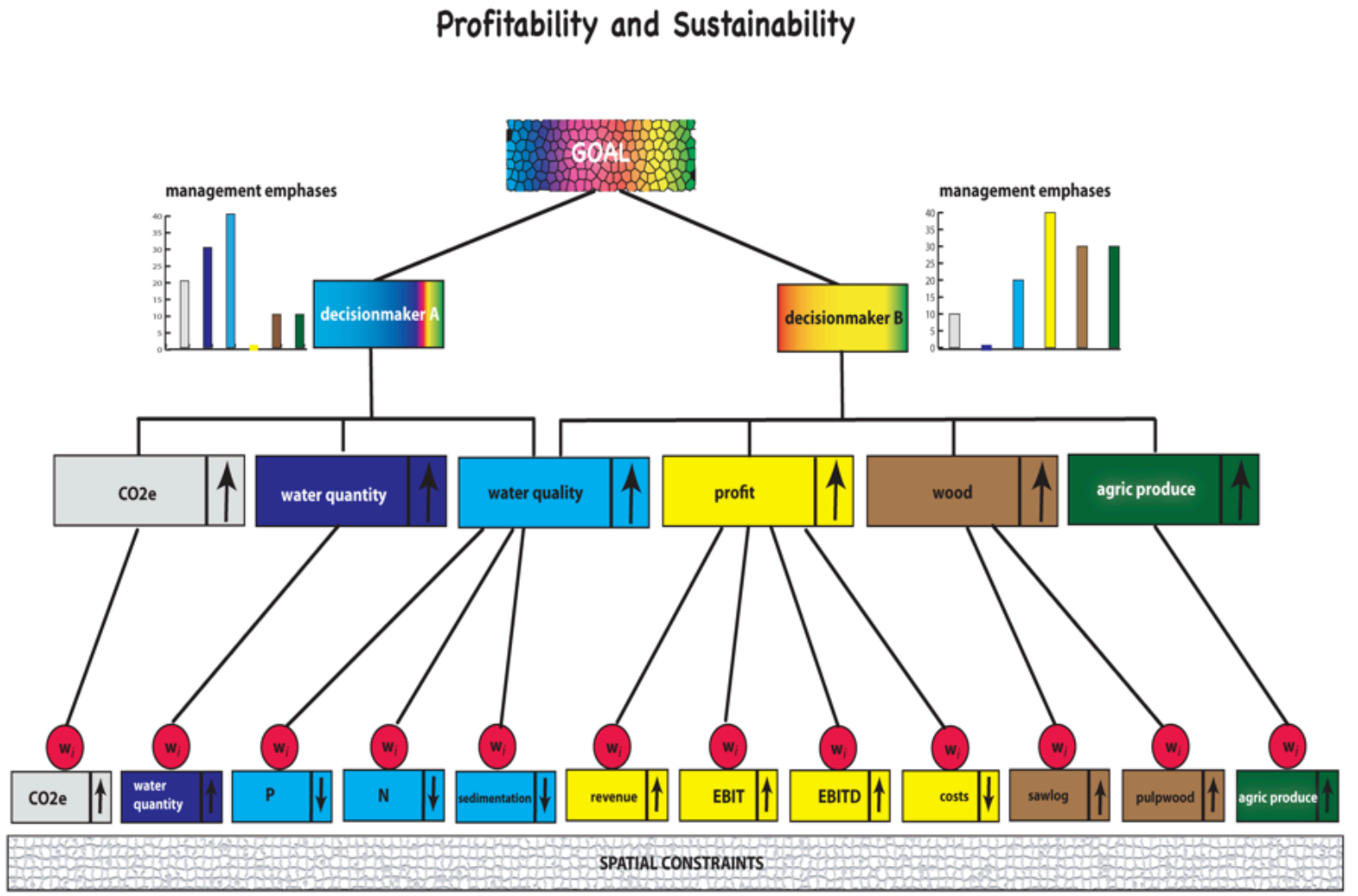


Wiley Practice Prize Winning Application (June 2013)

Principle applicable to other "Wicked" societal/industrial problems

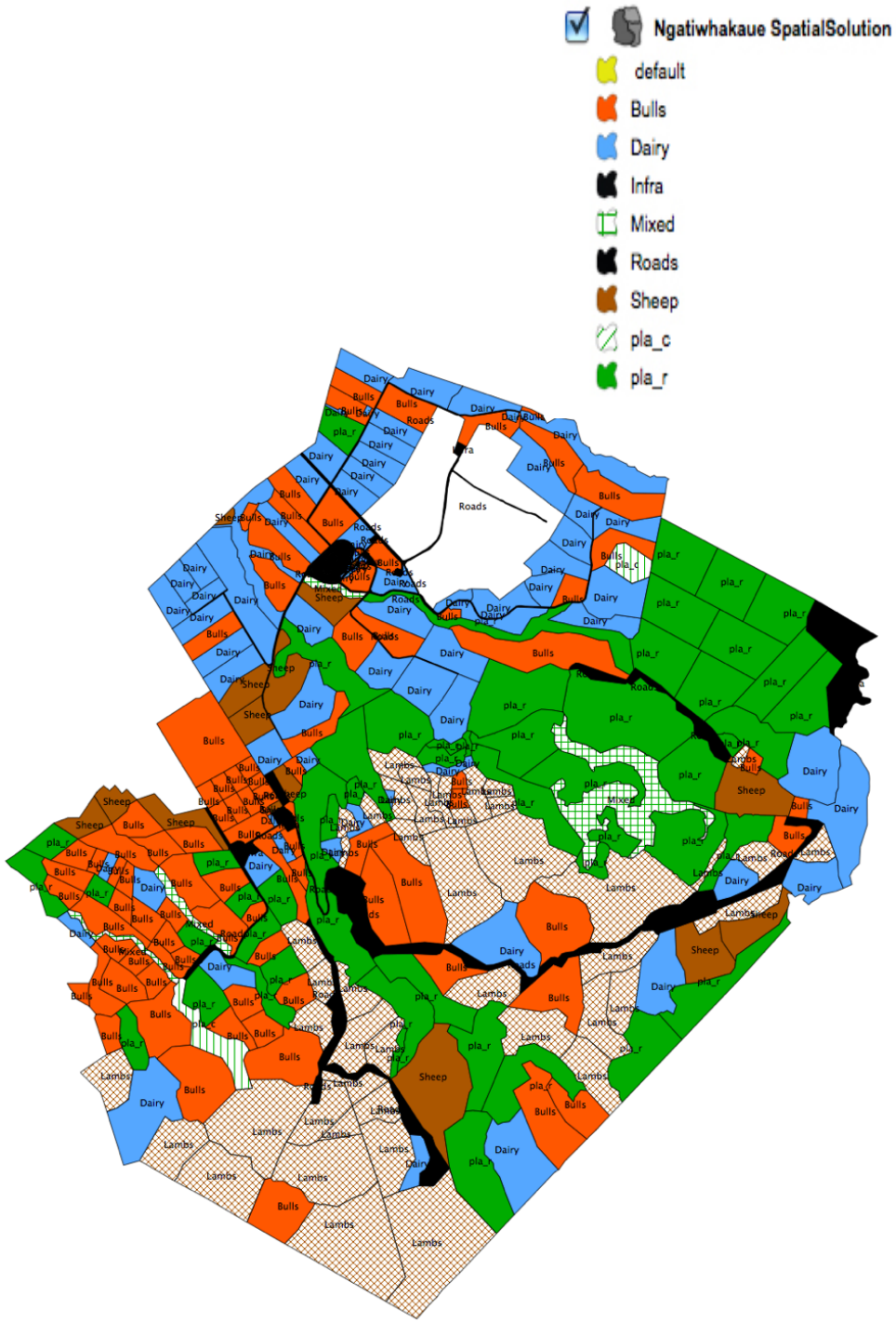
Chikumboo, O., Goodman, E., Deb, K. (2015). Triple bottomline many-objective-based decision making for a land use management problem. *Journal of Multi-Criterion Decision Analysis, 22*(3-4), 133–159.

14 Objectives – about profitability, production, and environment



Astronomical Search Space

- The space of land-use plans:
  - 315 independently manageable paddocks
  - Each having around 100 choices
  - Planning for 10 years
- Huge search space
  - $(100^{315})^{10}$ solutions
  - $\sim 10^{82}$ atoms in the universe
- Large number of objectives



Financials

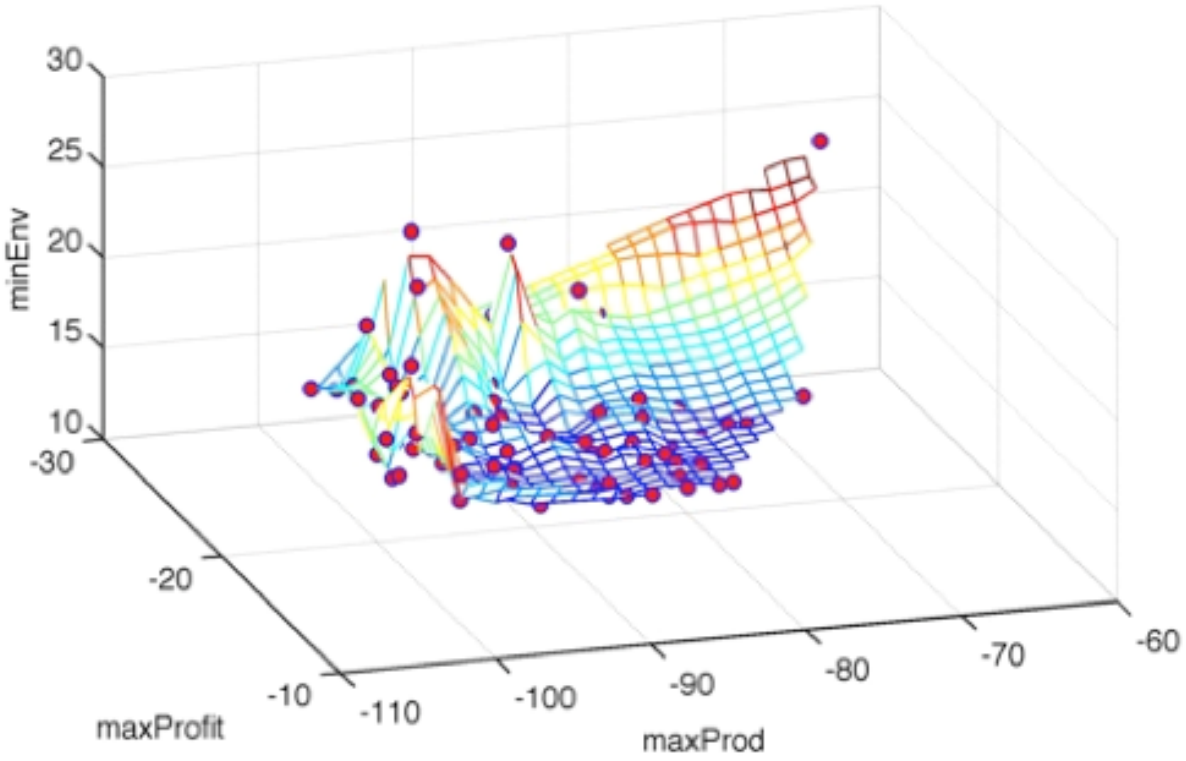
Productivity

Environment

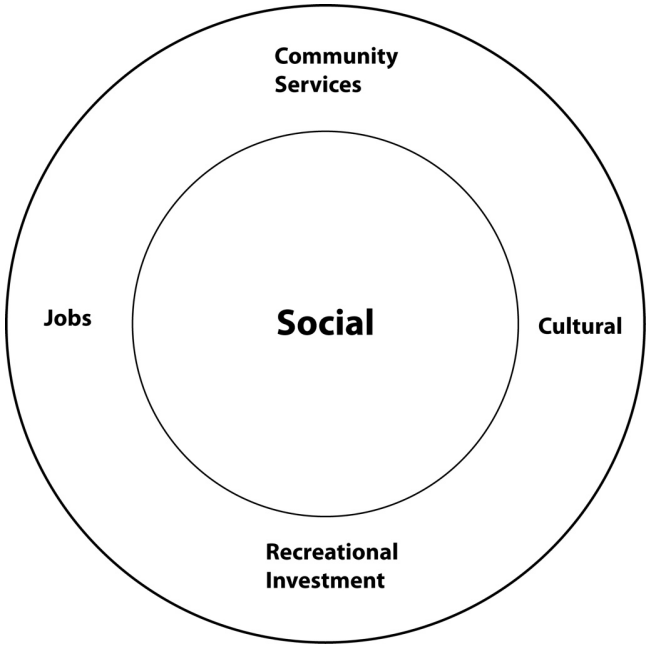
Pareto front =

f(MaxProfit, MaxProd, MinEnvImpact)

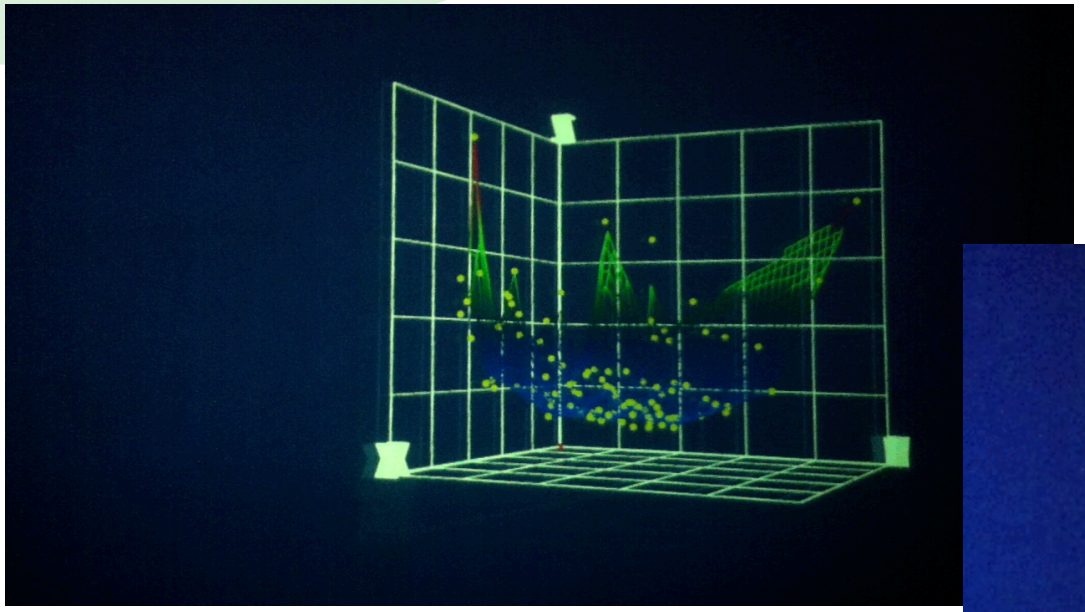
Developed WISDOM Approach using a customized EMO
A Typical Result:

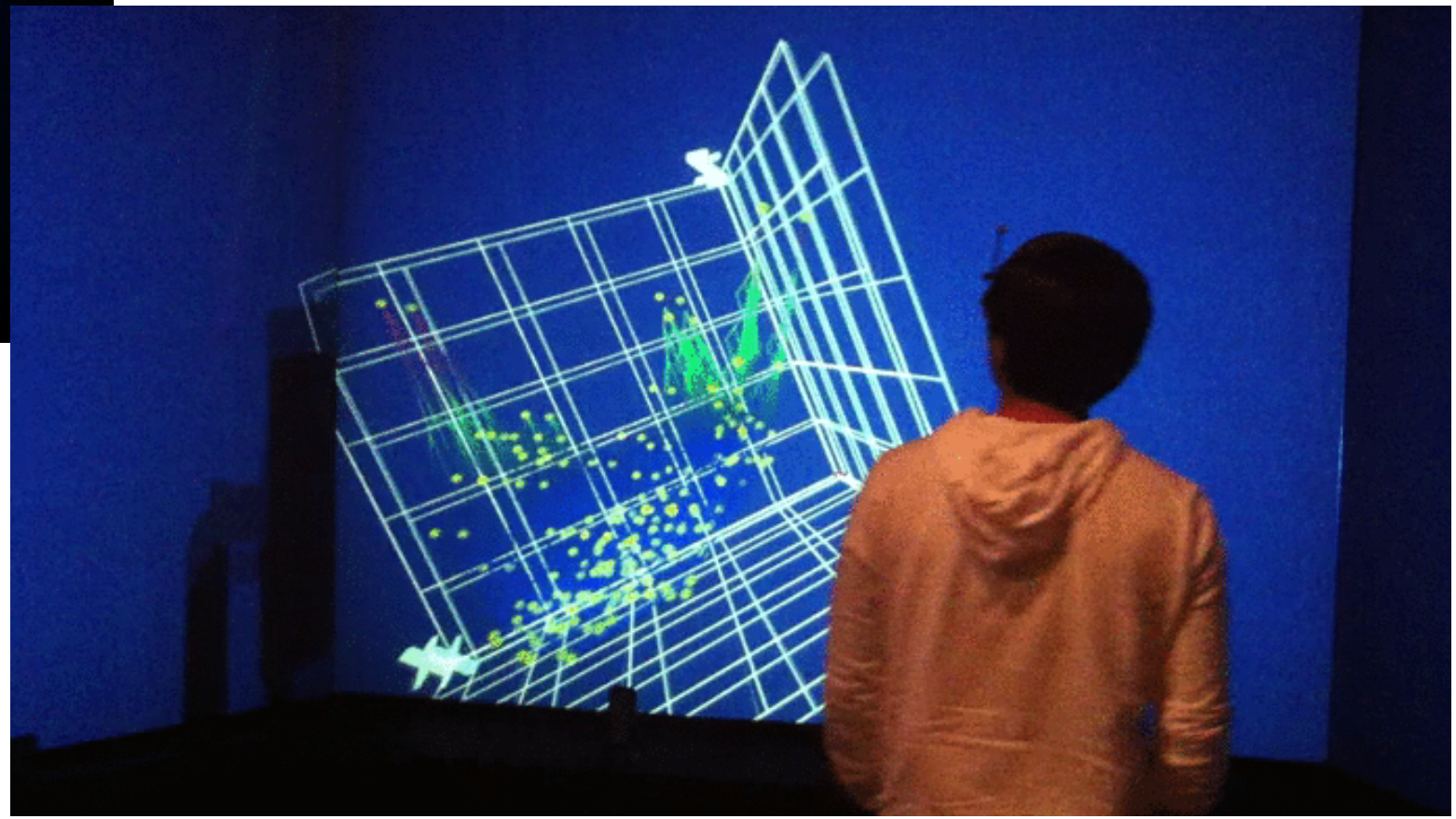


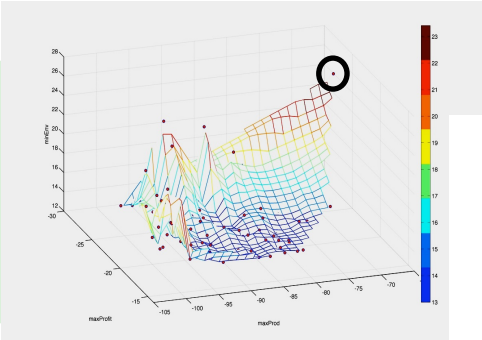
Decision-making later



Visualization Tools to Help Understand Trade-off (A VR-based System Developed)

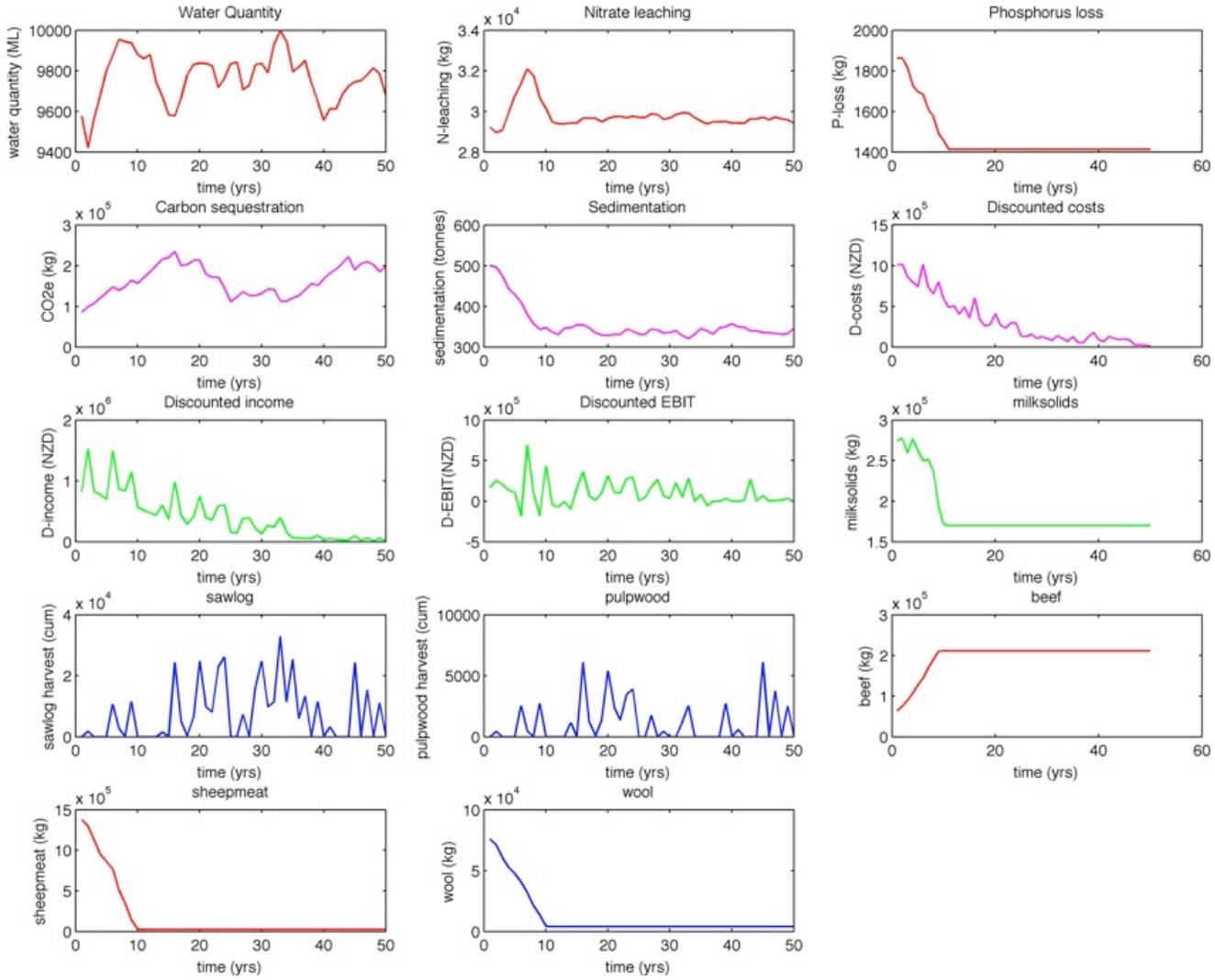






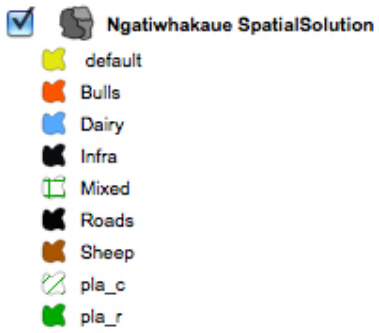
Environment-friendly Solution

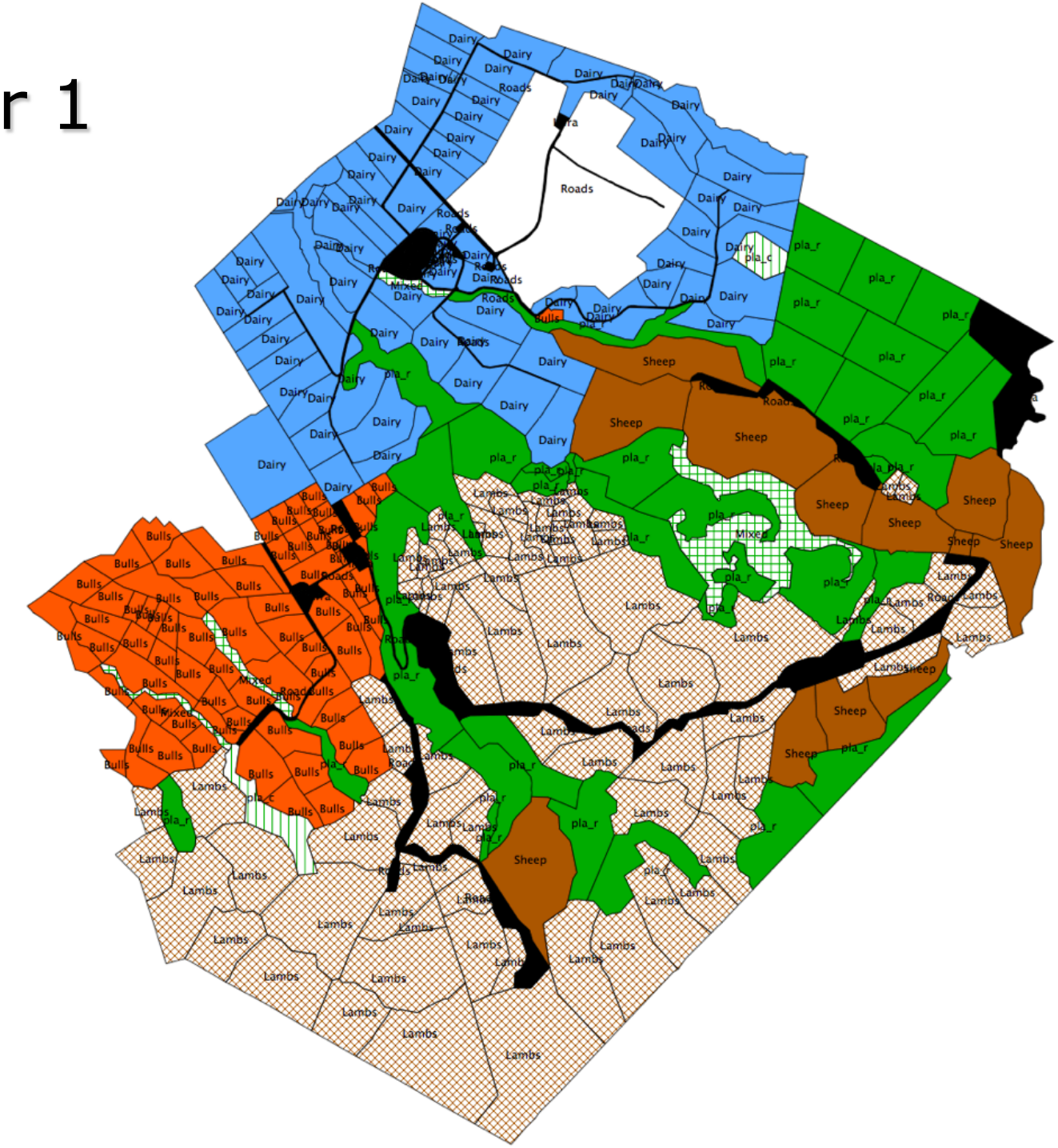
- Sheep substantively lower;
- Dairy drastically reduced;
- More and less frequent forest harvesting;
- Substantial increase in beef cattle.



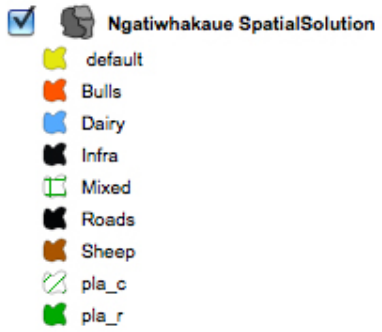
Spatial: year 1

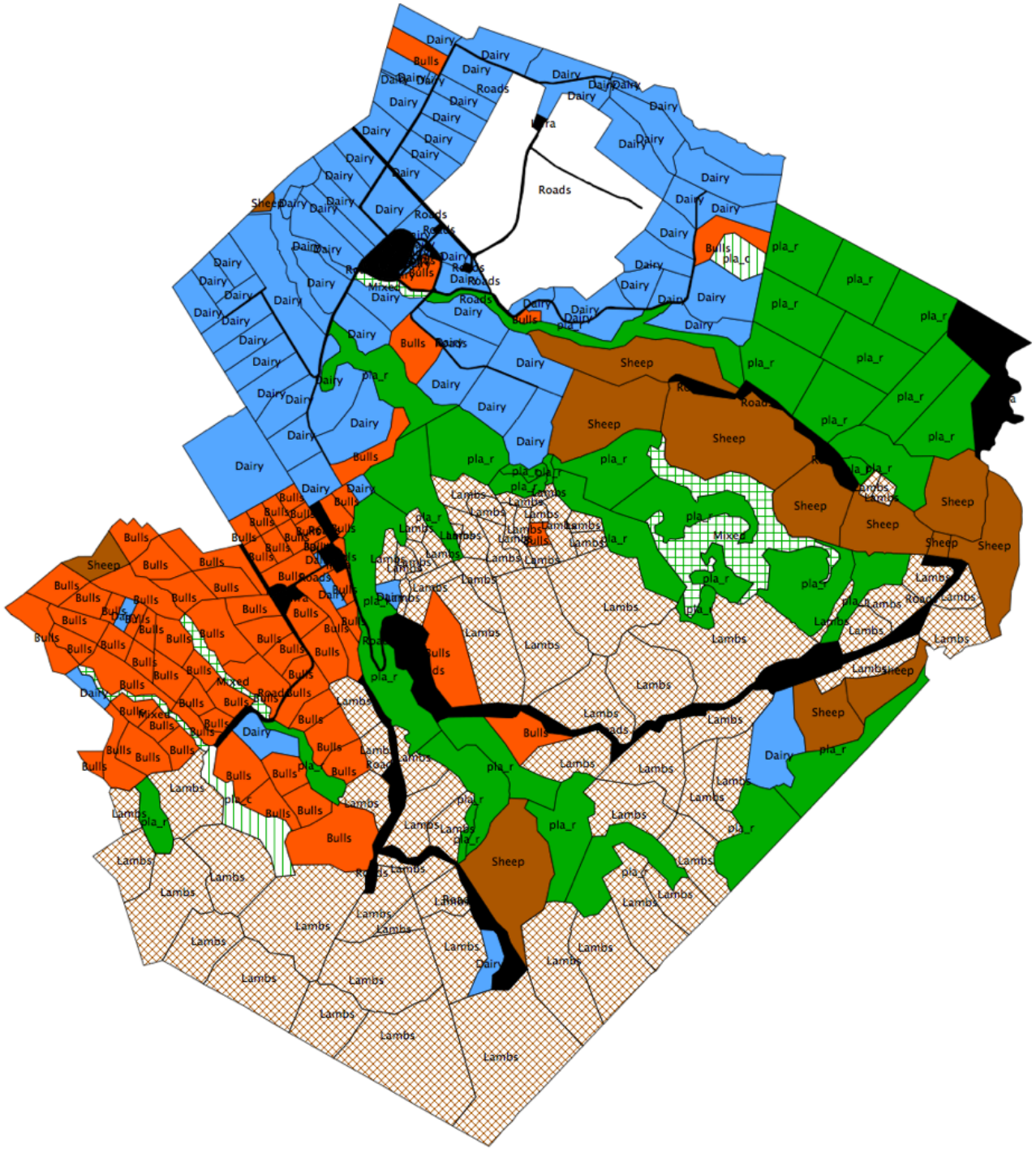
Solution 1



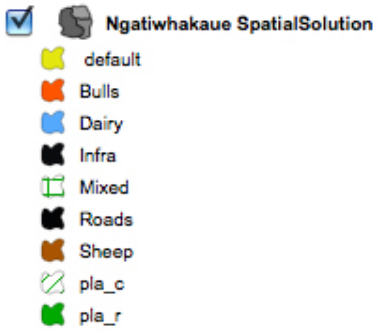


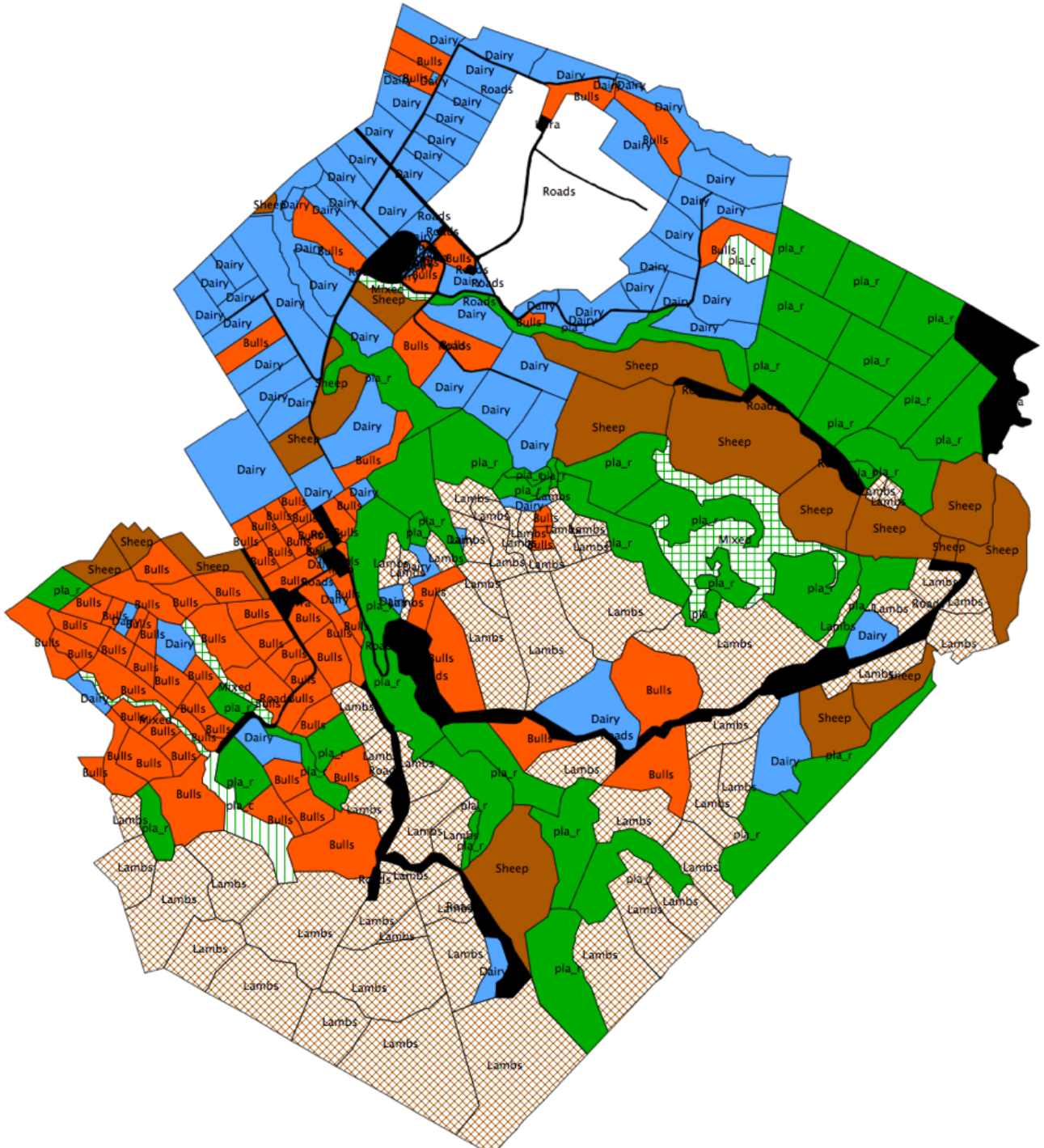
Spatial: year 2



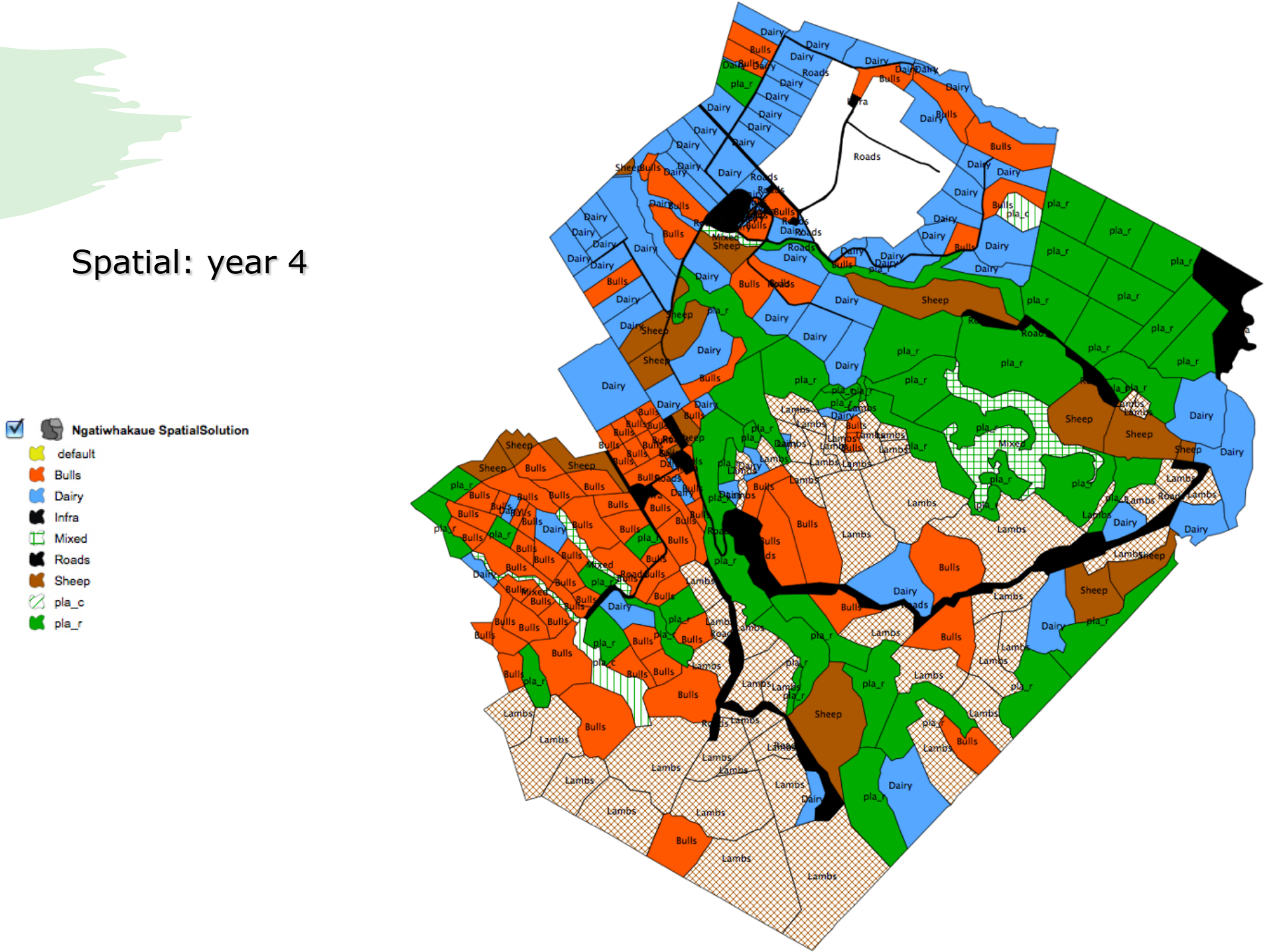


Spatial: year 3

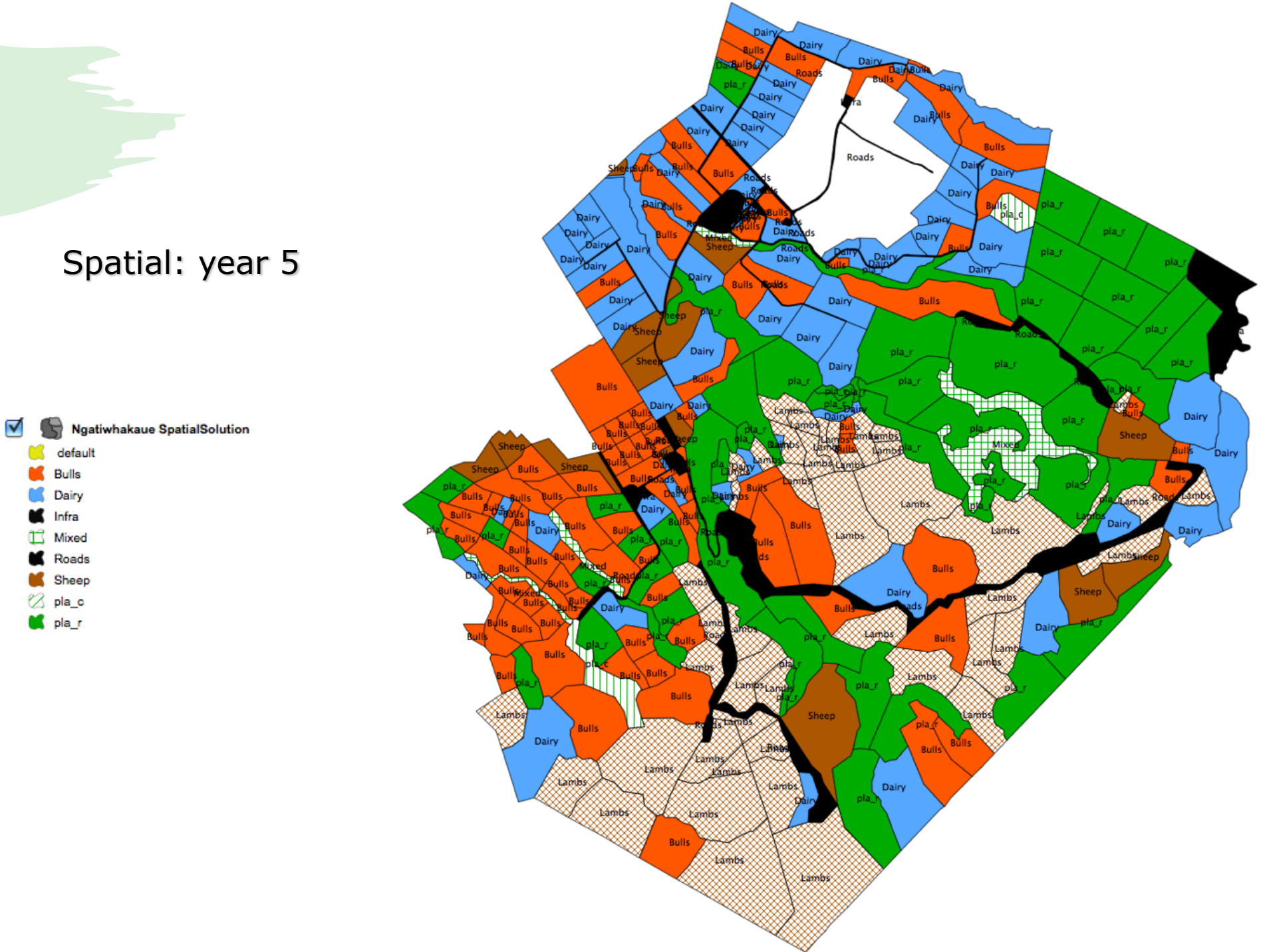




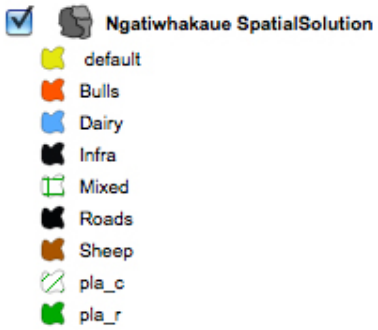
Spatial: year 4

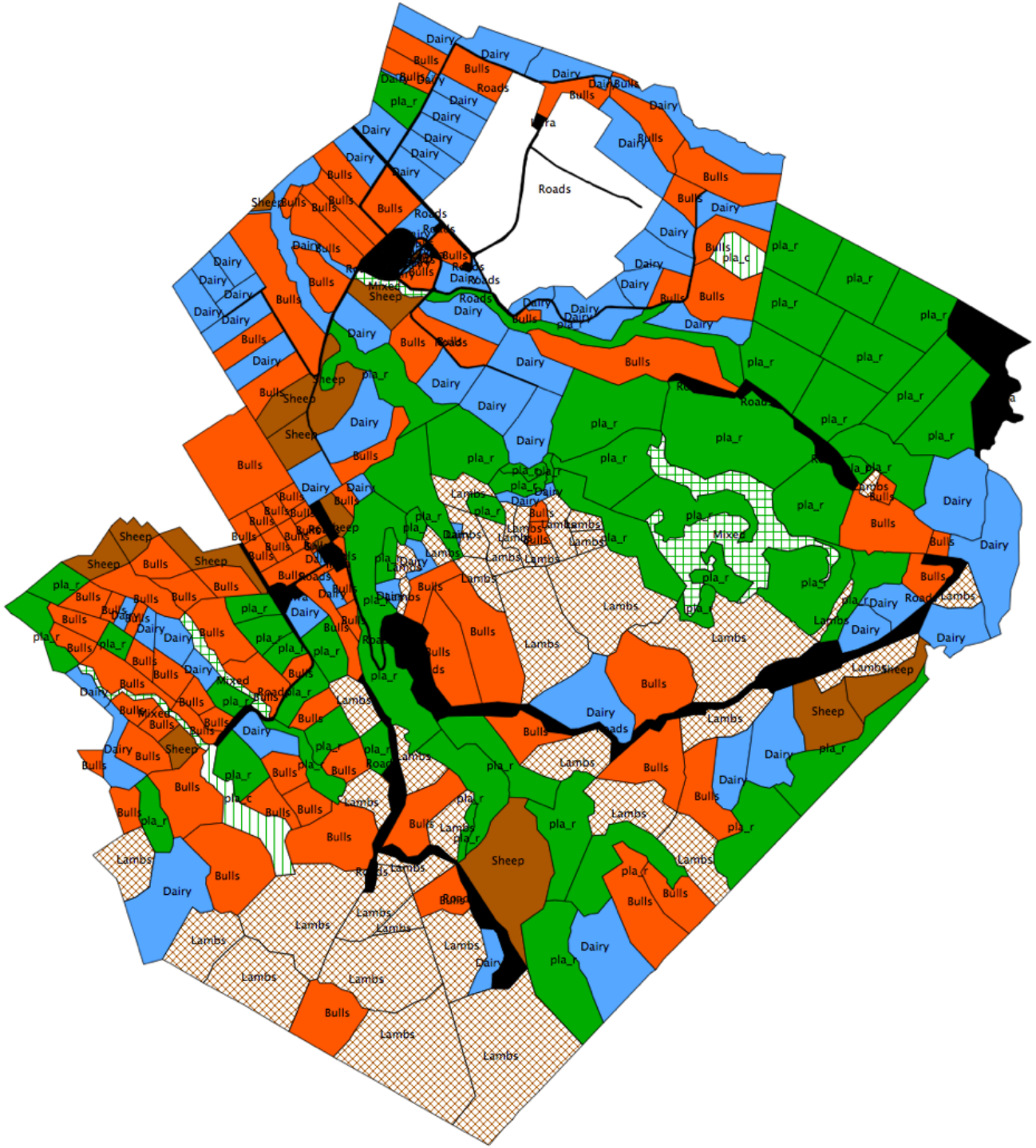


Spatial: year 5

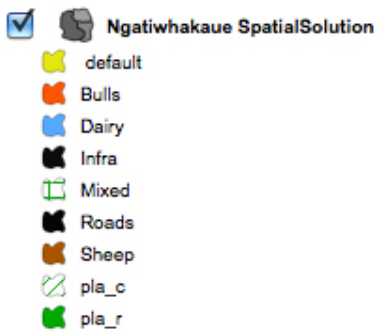


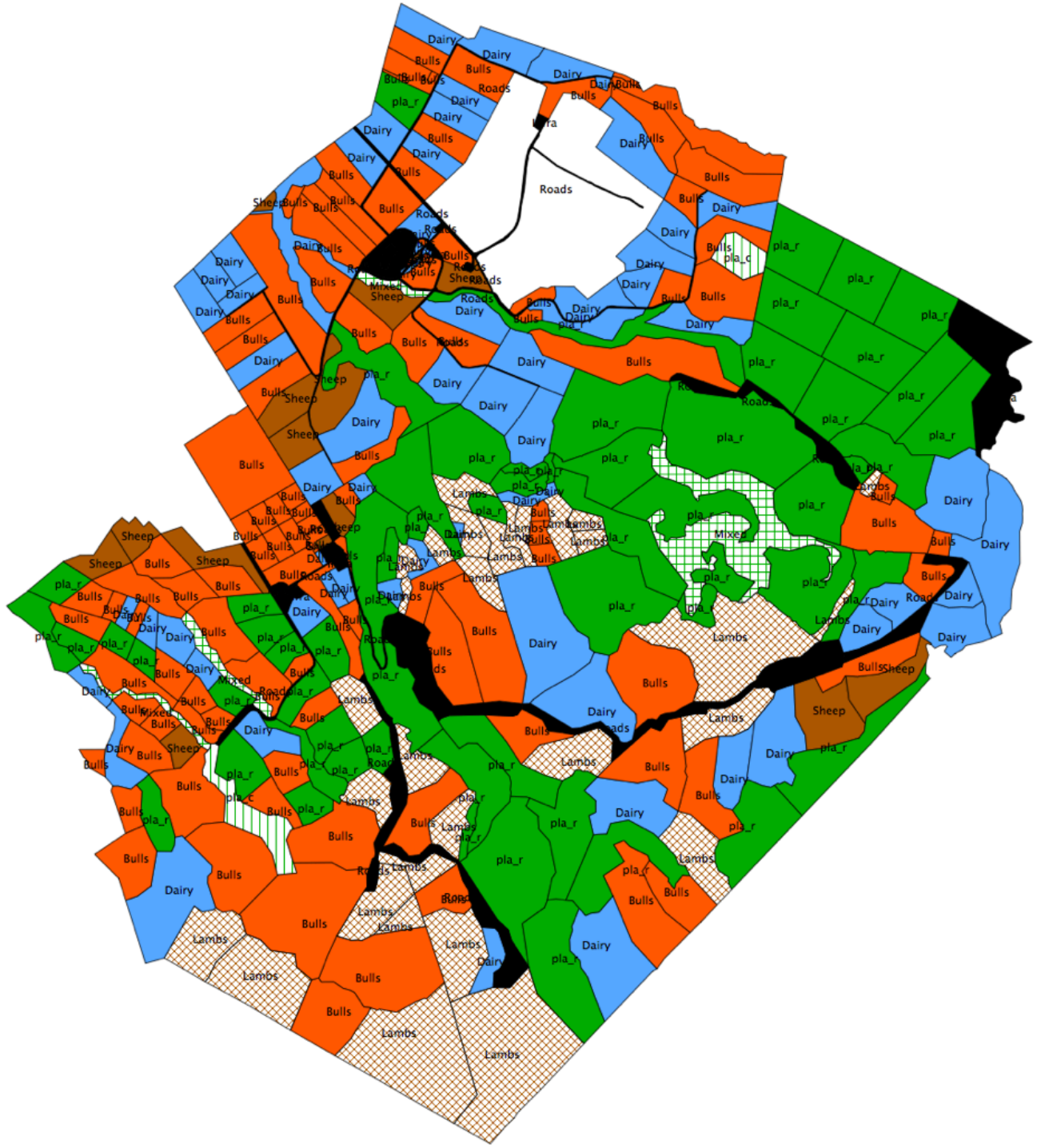
Spatial: year 6



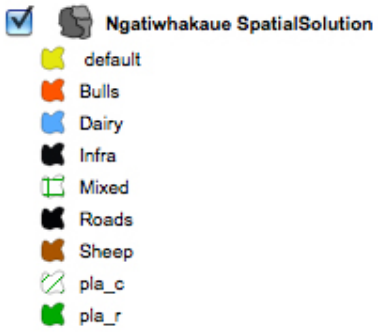


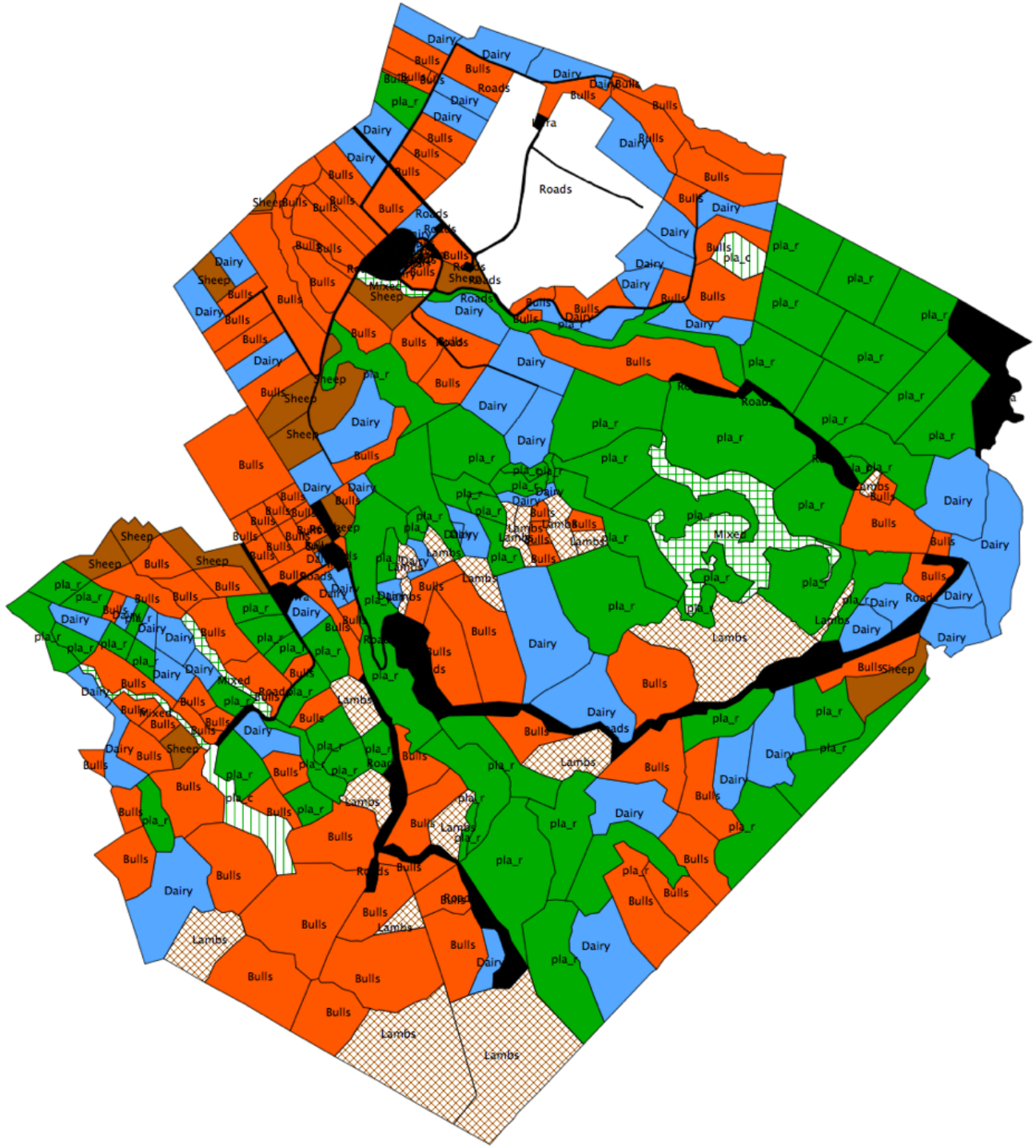
Spatial: year 7



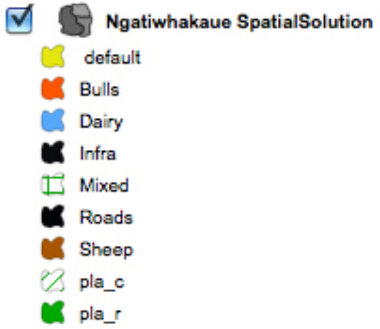


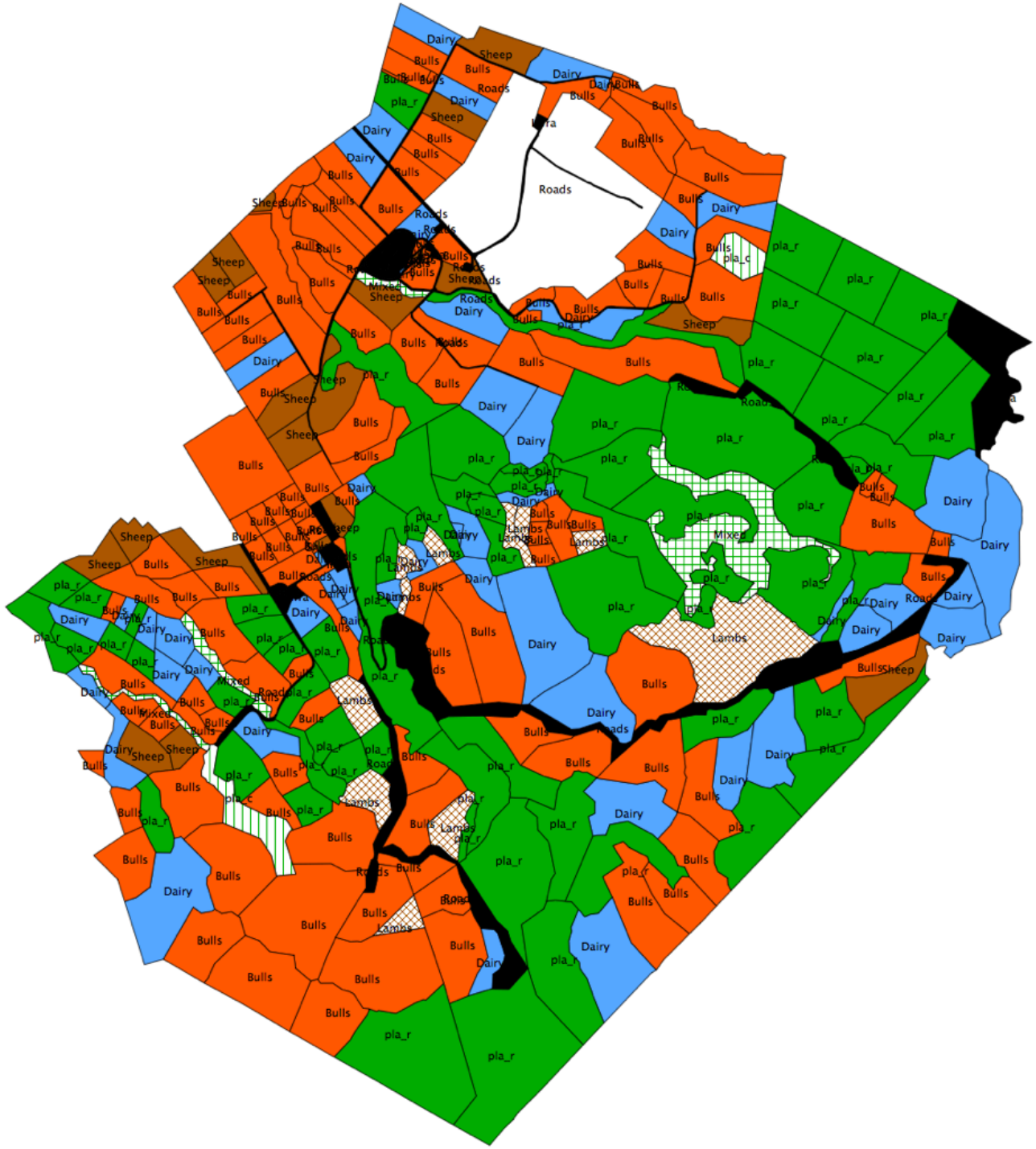
Spatial: year 8



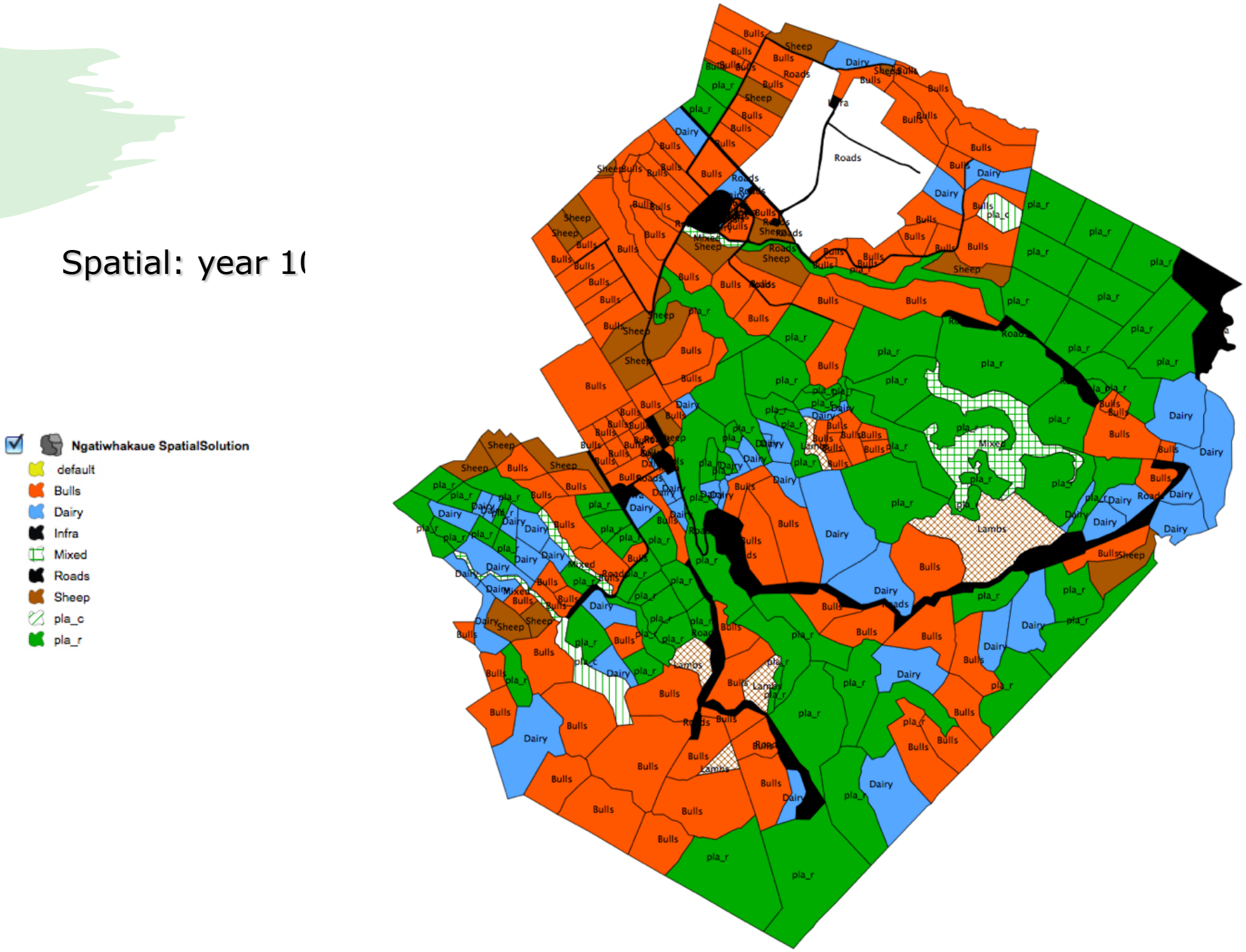


Spatial: year 9

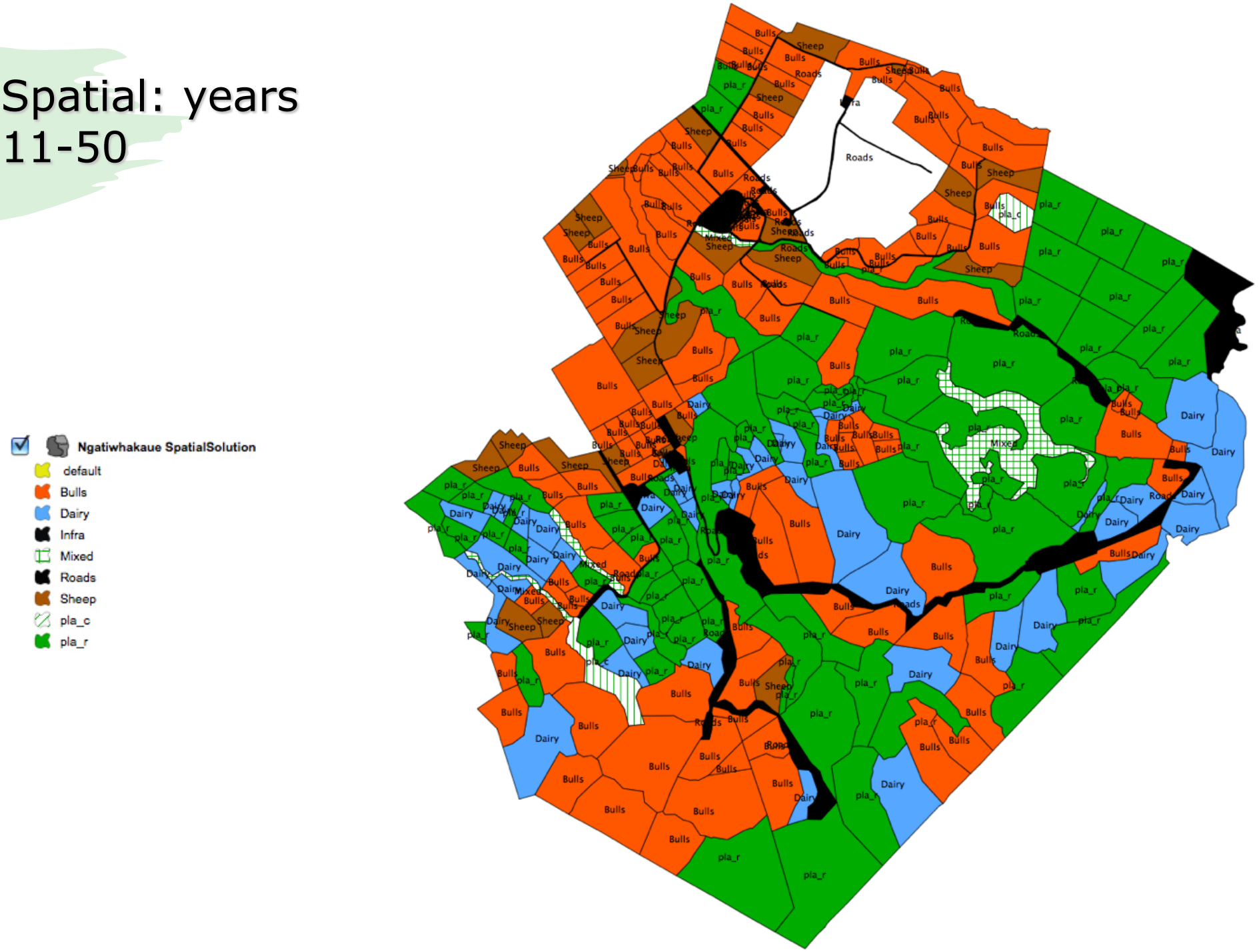




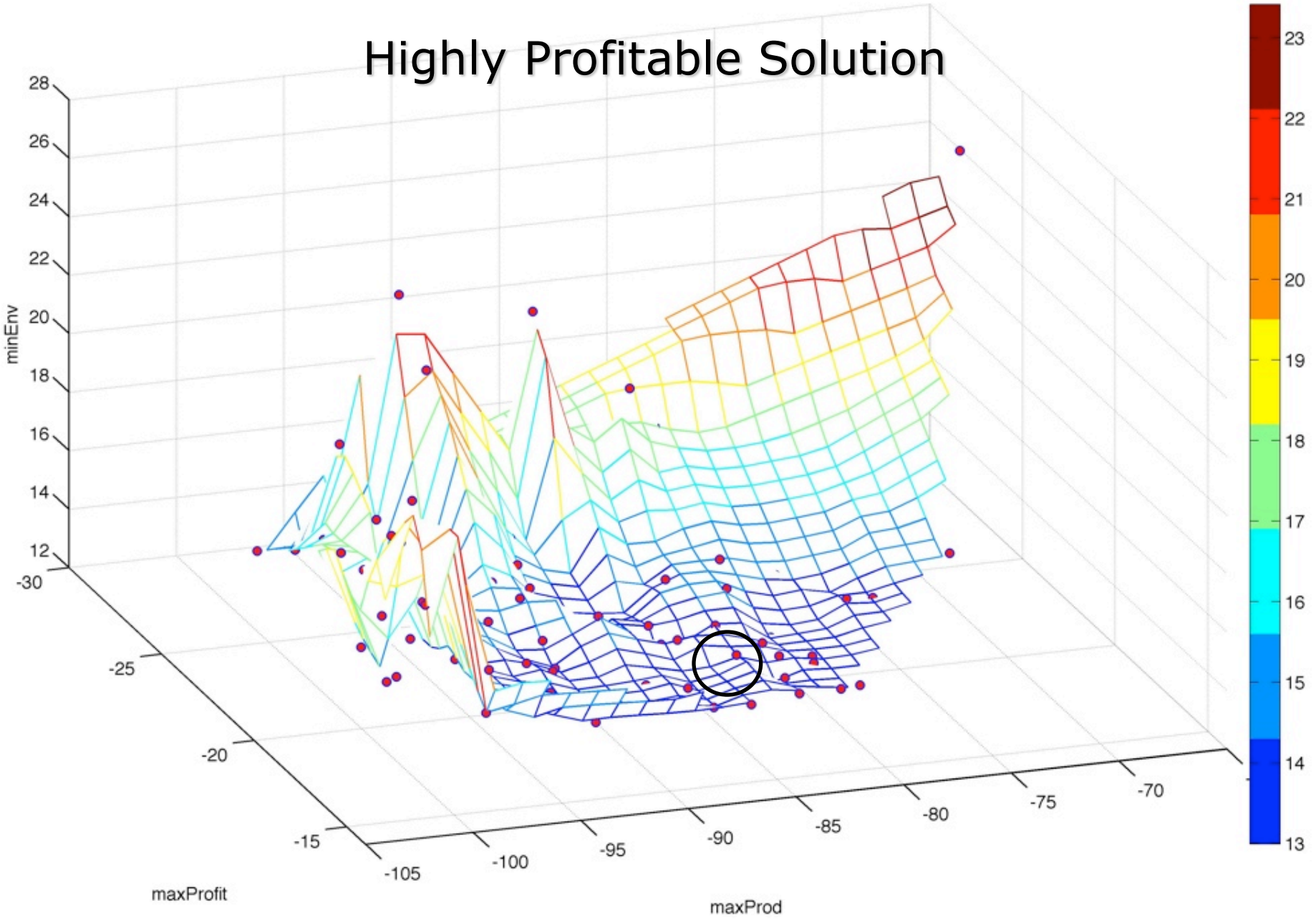
Spatial: year 1(



Spatial: years 11-50

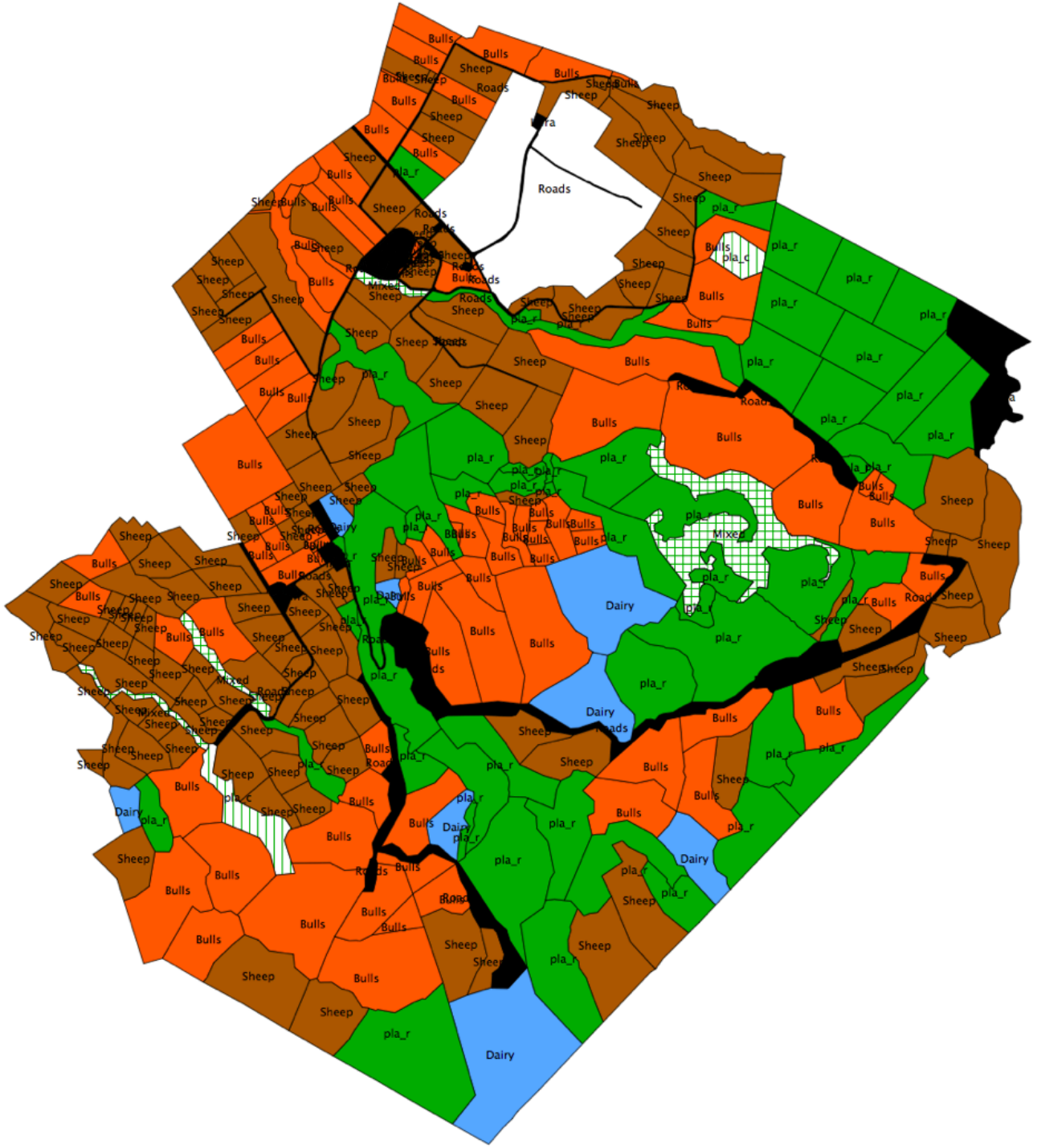


Highly Profitable Solution

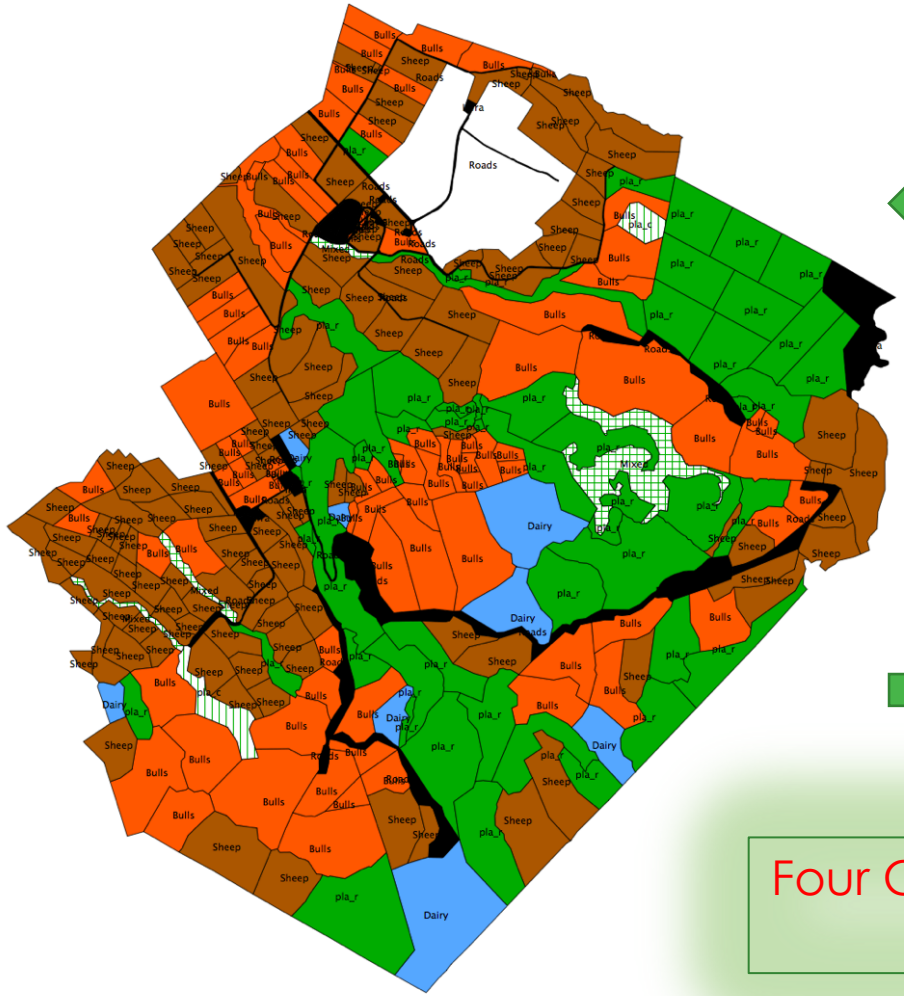


Spatial: years 11-50

solution 20



Highly profitable solution



Maori DMs

100 Intermediate Solutions Exist

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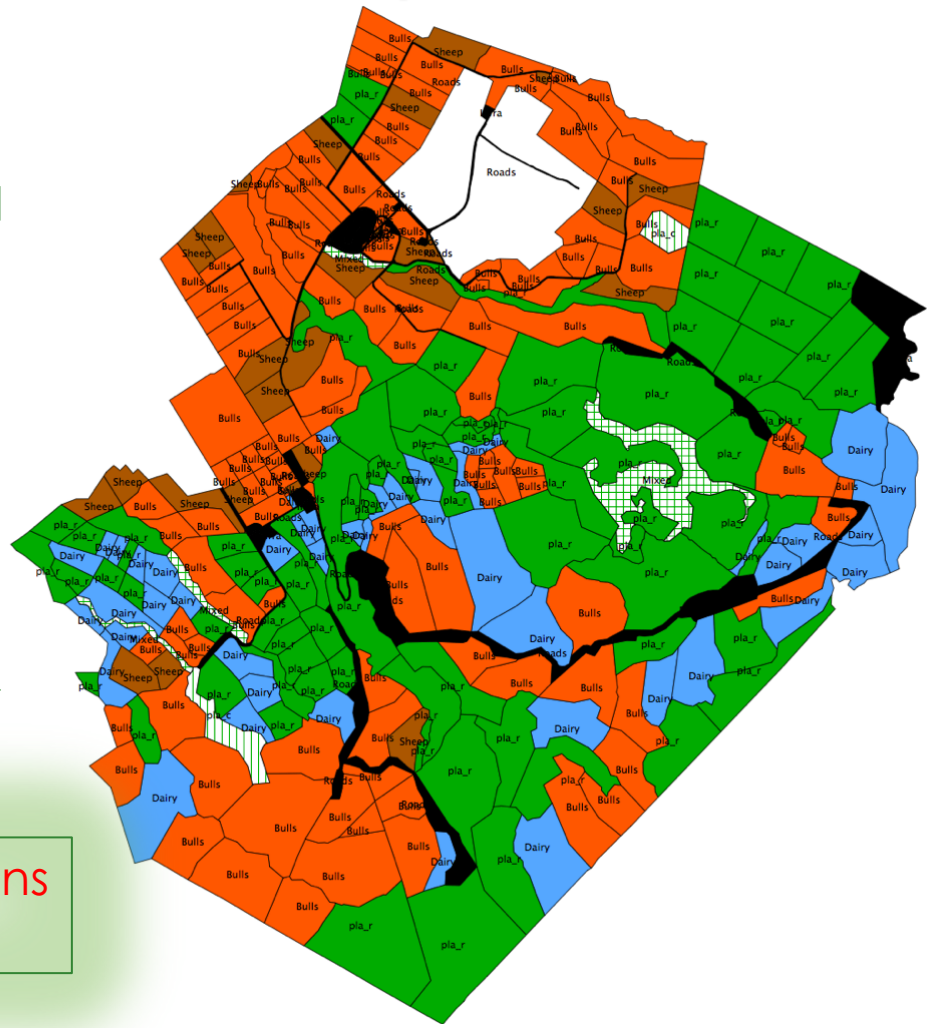
Government DMs

Four Compromised Solutions Found

"Environmentally friendly" solution



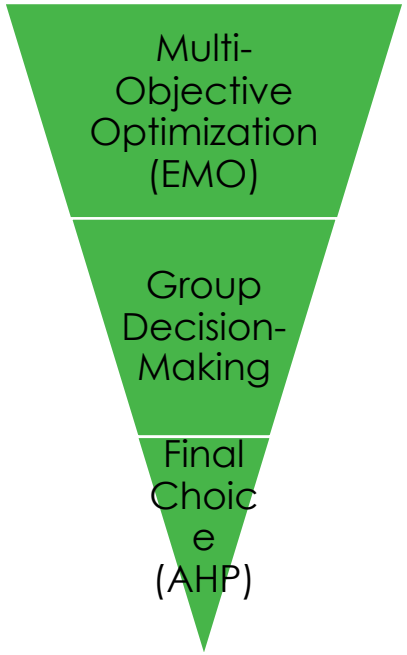
The Maori participants told the government that WISDOM is how they wanted to do future planning

Final Decision-Making with Four Solutions

- Four Stake-holder Groups:
  - Maori landowner, Rotorua district planner, Senior Waikato regional planner, and two senior forest planners
  - Each interview took 90-120 min
- **Analytical hierarchy process** (AHP) to decide on one preferred solution
  - Pair-wise comparison by stake-holders
  - An analytical process, thereafter

Final AHP Process & Solution

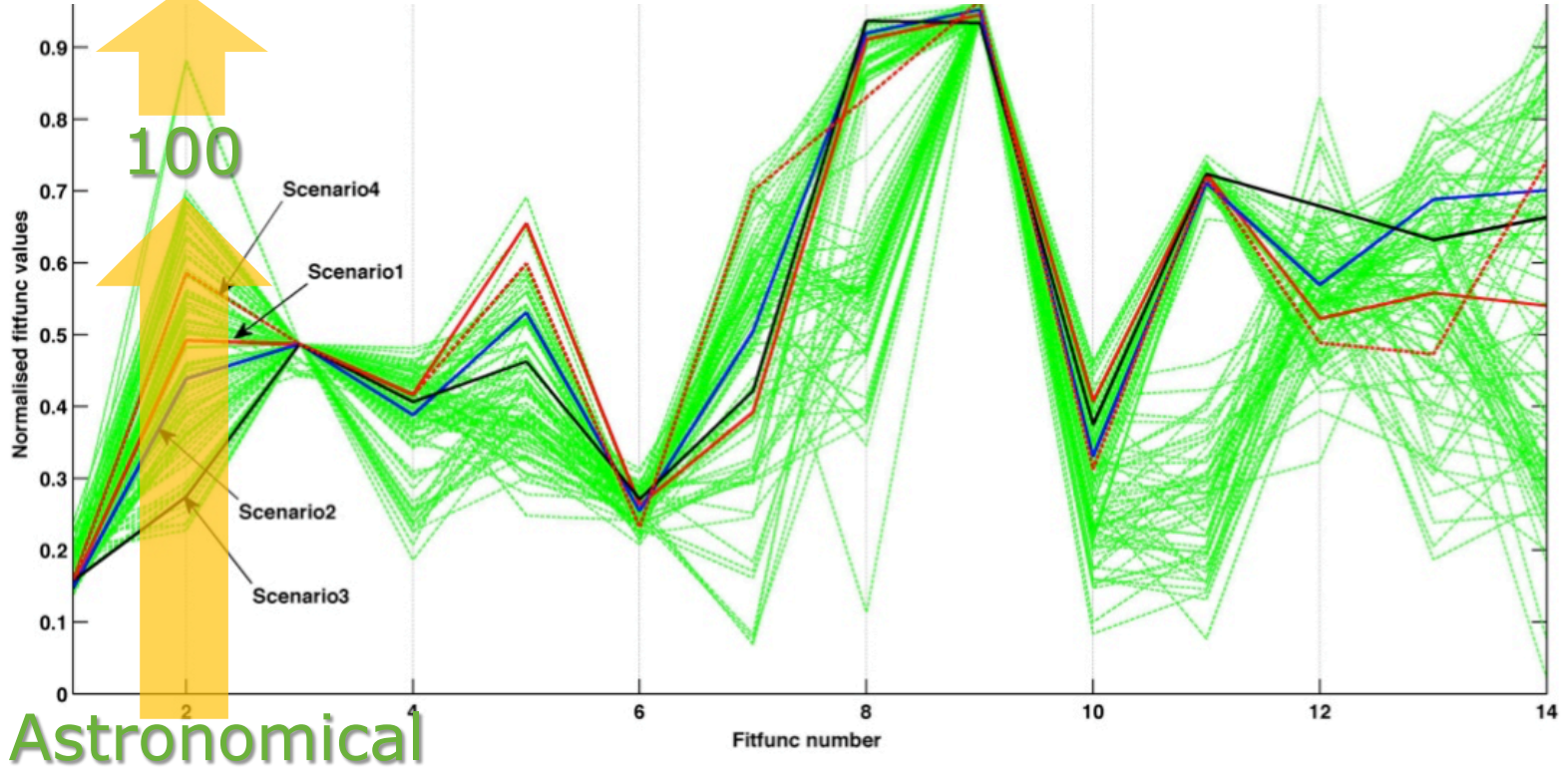
- Pair-wise decision-making by a group
- One of Four solutions chosen



SCENARIOS	PRIORITIES	IDEALISED PRIORITIES
1	0.1663	0.7387
2	0.1774	0.7882
3	0.2251	1
4	0.1345	0.5971

WINNER

100

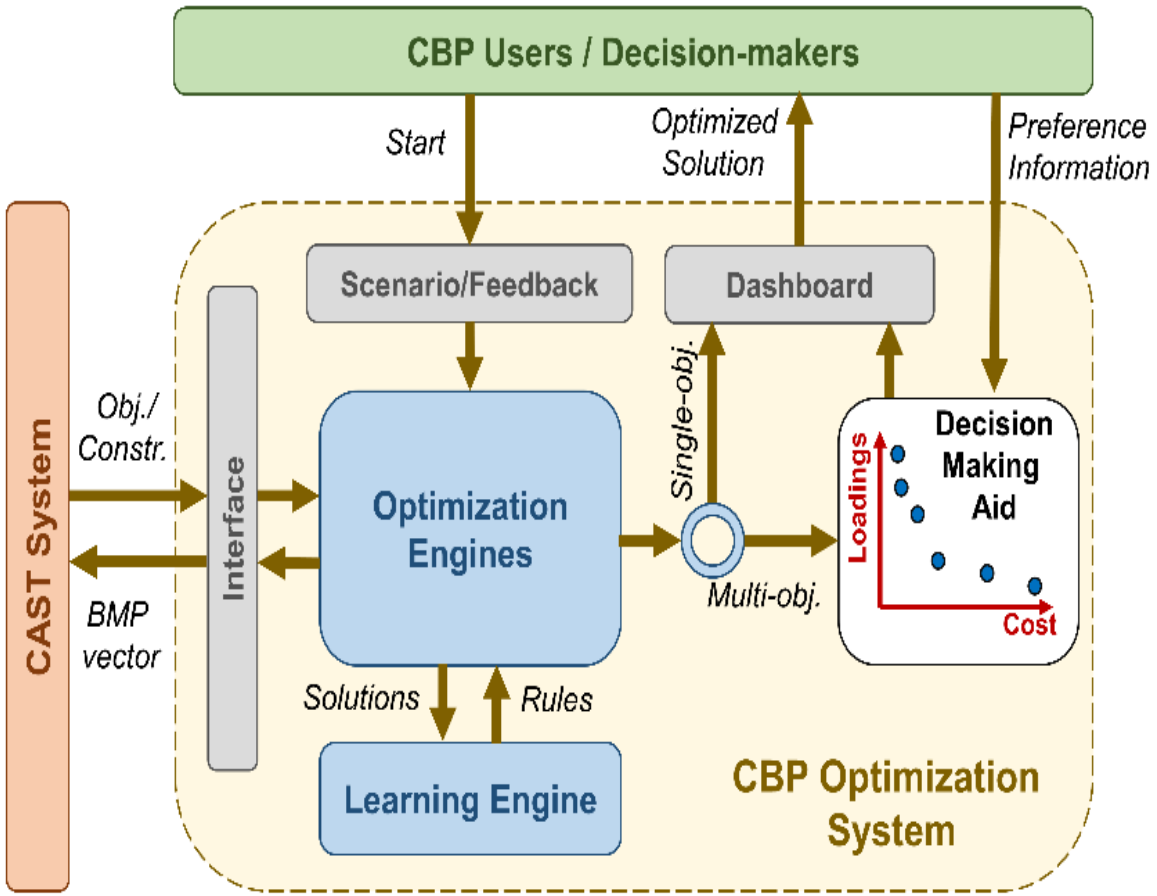


Astronomical

EPA Optimization Project Plan (6 years)

- Develop efficient optimization algorithms
  - Integration with CAST system
  - County, multi-county, state, multi-state, and watershed level
  - Hybrid and customized approach
- Min. Cost subject to Loading constraints
- Multi-objective: Min. (Cost, Loadings)
  - MCDM with stake-holders
  - Robust solutions
  - Knowledge-based optimization
- Implementation through validation and discussion with CBP users

Overall Plan



CAST System and Optimization: Overall Project Plan (2020 – 2026)

- Objective 1 (First 18 mths.): *Single-objective, customized, hybrid optimization methods* and scalability study, state-level
  - IPOPT made faster through customization
- Objective 2 (Next 18 mths.): Multi-objective, customized, hybrid optimization methods and multi-criterion decision-making aids
- Objective 3 (Next 18 mths.): Scalability study to multi-state and watershed level with Distributed computing and AI-based learning from optimization (*Innovization*)
- Objective 4 (Final 18 mths.): Handling practicalities using robust, surrogate-assisted, and sustainable optimization methods
- Will communicate results in regular meetings

Thank you for your Attention!