Simulation Optimization Lab

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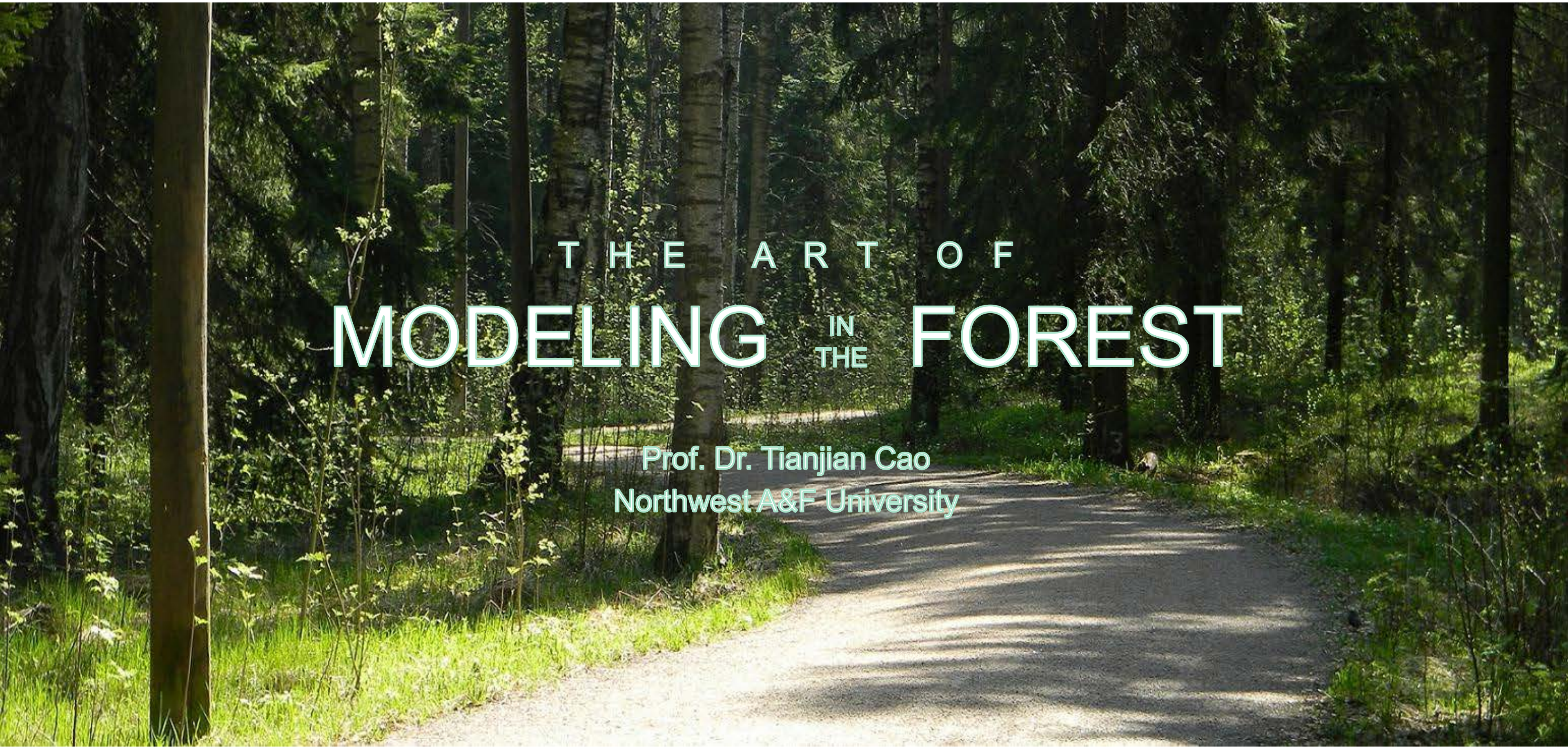


THE ART OF MODELING IN THE FOREST

Prof. Dr. Tianjian Cao
Northwest A&F University

OPTIFOR

2024.12, 智慧林业研讨课

QUASSI

Contents

生态仿真优化实验室
Simulation Optimization Lab

智慧林业: 从监测、预测到决策

Smart Forestry

from

Observation, Prediction, to Decision

IT技术发展的三个阶段

- 第一代IT (Industrial Technology),
  - 机电一体化,
  - CIMS,
  - …
- 第二代IT (Information Technology),
  - 数据库,
  - 电算化,
  - …
- 第三代IT (Intelligence Technology),
  - 大数据,
  - 大模型,
  - 数字孪生,
  - …

AI技术发展的三个阶段

- 1st generation AI: Fundamental Algorithms
  - Random number generators, K-means clustering
  - Simulated annealing, Nelder-Mead algorithm
- 2nd generation AI: Nature-Inspired Algorithms
  - Evolution algorithm, Genetic programming
  - Particle swarm optimization, Ant colony optimization
  - Cellular automata
- 3rd generation AI: Neural Networks and Deep Learning
  - Machine learning, Artificial neural network
  - Convolutional neural network, Natural language processing

AI技术应用产业链

- 1. 顶层设计与系统架构
- 2. 硬件设备与工业生产
- 3. 精密仪器与电子测量
- 4. 智能装备嵌入式开发
- 5. 系统集成与网络运维
- 6. 数据采集与模型训练
- 7. 模型优化与模型更新
- 8. 工程部署与监管部门
- 9. 数据安全与闭环管理
- 10. 国产化政策与Linux

AI技术应用场景

- 1. 数字信号
- 2. 网络通信
- 3. 视觉识别
- 4. 集成电路
- 5. 机器人
- 6. 3D打印
- 7. 自动控制
- 8. 边缘计算
- 9. 无人驾驶
- 10. 智慧交通
- 11. 智慧建筑
- 12. 虚拟现实
- 13. 数字孪生
- 14. 智慧物流
- 15. 智慧仓储
- 16. 电子商务
- 17. 智慧金融
- 18. 电子政务
- 19. 智慧城市
- 20. 智慧应急
- 21. 智慧园区
- 22. 智慧校园
- 23. 智慧家园
- 24. 智慧医疗
- 25. 智慧矿山
- 26. 智慧化工
- 27. 智慧水利
- 28. 智慧农业
- 29. 智慧牧业
- 30. 智慧林业

智慧林业发展的四个阶段

- 1. 林业信息化，
  - 数据库, 森林资源GIS图
- 2. 林业3S,
  - GIS, RS, GPS/GNSS/BD?
- 3. 数字林业,
  - GIS, RS, LiDAR，无人机
- 4. 智慧林业,
  - 数字孪生, 仿真模型? 优化算法?

Introduction 森林建模学科体系

- 林业经济 Forest Economics
  - 计量经济模型 Econometric models
  - 生物经济模型 Bioeconomic models
- 森林经营 Forest Management
  - 生物统计模型 Growth and yield
  - 决策支持系统 Forest planning
- 森林生态 Forest Ecology
  - 生物统计模型 Biometric models
  - 过程机理模型 Process/mechanistic models
- 森林工程 Logging and transportation
  - 出材优化模型 Log merchandizing models
  - 采运集材模型 Forest transportation

生态仿真优化实验室
Simulation Optimization Lab

Managing Natural Resources

From utilization, optimization, to evaluation

Spatial and temporal aggregation

Spatial scale

Biome shift models

Landscape — Landscape models

Community — Succession models

Population — Stand models

Organism — Individual tree models

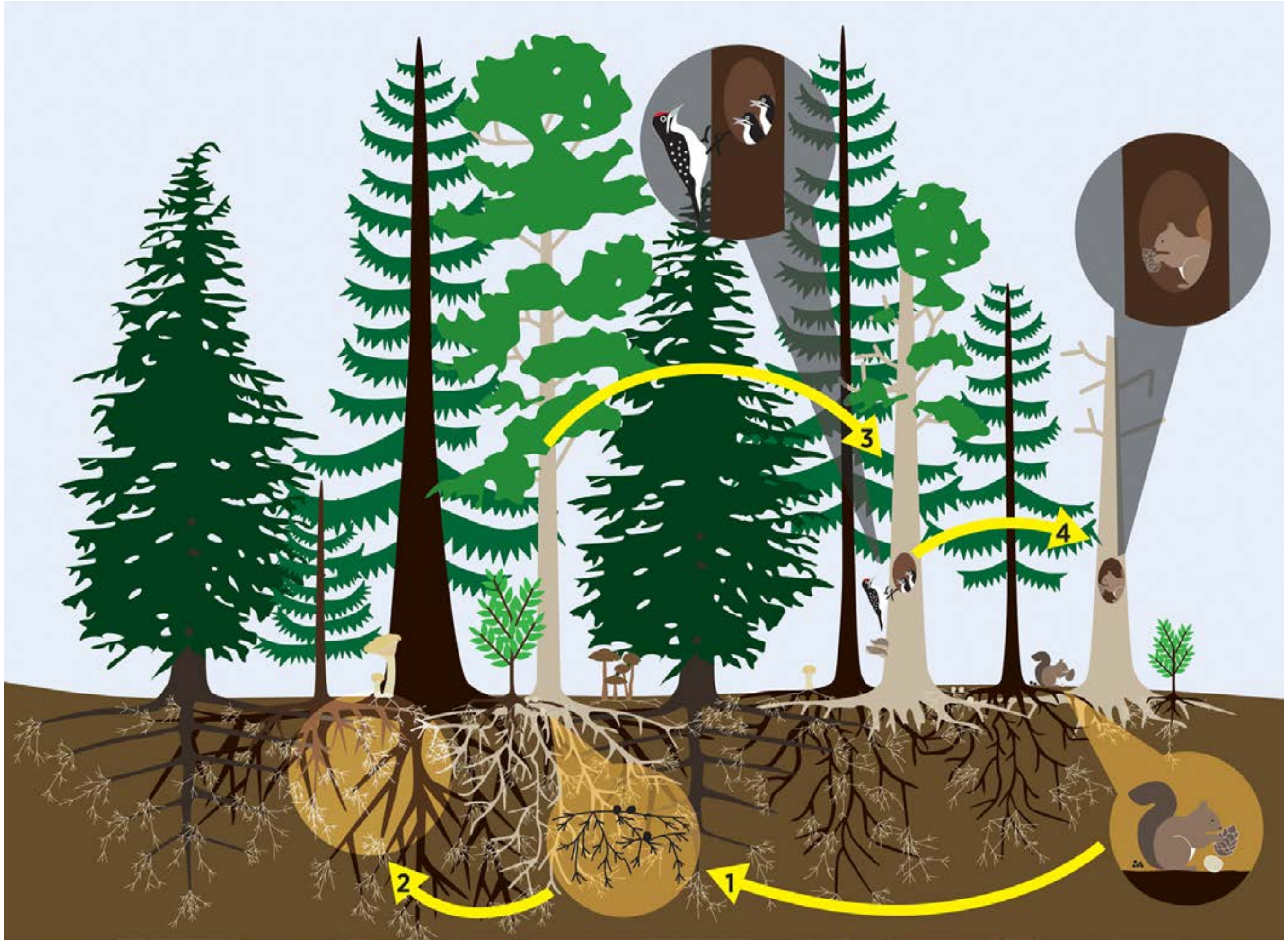
Organ — Ecophysioligical models

Cell

Second Day Year Decade Century Century Millenium

Temporal scale

A self-organizing meta-network



Source: Filotas et al. (2014)

Forest and Natural Resources

Natural Resources

- Agriculture
- Fisheries
- Mining
- Water resources
- **Forestry**

Natural resources as complex systems

- 1 Heterogeneity, 2 hierarchy,
- 3 self-organization, 4 openness,
- 5 adaptation, 6 memory,
- 7 non-linearity, 8 uncertainty

Virgin forests in the Rocky Mountains

OR in Agriculture

- Agriculture problems:
  - Risk management
  - Interaction between agriculture and the environment
  - Water resources planning
  - Agroforestry systems management
  - Simulation of effects on changes of agriculture policy
- OR/MS techniques used:
  - Linear programming
  - Multi-objective fractional programming
  - Goal programming
  - Multi-attribute utility theory
  - Control dynamic optimization

OR in Fisheries

- Fisheries management
- Shared fish stocks and high seas issues
- Game theoretic applications to fisheries
- Uncertainty in bioeconomic modelling
- Parametric and non-parametric techniques
- Demand structure for fish and seafood products

OR in Agriculture, Fisheries, Forestry

- The same self-thinning rule
  - Optimal stocking control
    - Over grazing
    - Fish farming
    - Forest stand density

- The different time scale
  - The length of rotation
    - Months: Agriculture
    - Years: Fisheries
    - Decades: Forestry

Is there a more efficient way?

Simulation

Biometrics

Optimization

Algorithms

Spruce-beech forests in Bavaria

The Faustmann Formula（1849）

- Present Value of Bare Land

$$PV_{timber} = \frac{e^{-rt}\left[B(T) - c\right]}{1 - e^{-rt}}$$

- Optimality Condition

$$\frac{B'(T)}{B(T) - c} = \frac{r}{1 - e^{-rt}}$$

森林生长理论体系 Theory of forest growth

- 适地适树原则，Species-specific and site-specific

- 林木结构异速生长理论, Allometrics of tree architecture
- 林分结构概率分布理论, Probability distribution of stand structure
- 林木生长代谢尺度理论, Metabolic scaling theory of tree growth
- 林分密度自然稀疏理论, Self-thinning theory of stand density
- 森林更新林窗空间理论, Gap theory of forest regeneration

Equation set of forest growth 森林生长方程组

Equation set of forest dynamics

I	$w_i = \alpha \cdot w^{\beta}$	The allometric relationship of tree structure
II	$f(d_i) = f(A,S,D)$	The probability density function of stand structure
III	$\ln iv = \alpha + 3/4 \cdot \ln v$	The metabolic scaling theory of tree growth
IV	$\ln N = \alpha - 3/2 \cdot \ln V$	The -3/2 self-thinning rule of stand density control
V	$R = \alpha - \beta \cdot G + \gamma \cdot S$	The gap model theory of forest regeneration

森林动态方程组

I	$w_i = \alpha \cdot w^{\beta}$	林木异速生长定律
II	$f(d_i) = f(A,S,D)$	林分结构概率密度分布规律
III	$\ln iv = \alpha + 3/4 \cdot \ln v$	林木生长新陈代谢尺度理论
IV	$\ln N = \alpha - 3/2 \cdot \ln V$	林分密度自疏伐理论
V	$R = \alpha - \beta \cdot G + \gamma \cdot S$	森林更新林窗理论

OR in Forestry

- Tree-, stand-, and forest-level (*simulation*)
- Strategic-, tactical-, and operational-level (*optimization*)

- Log merchandizing and timber grading
- Forest logistics
- Forest wildlife preservation
- Spatial environmental concerns
- Forest management planning
- Forest policy and economics
- Multiple criteria decision-making
- Forest fire management
- Forest pests
- Adaptive forest management

OPTIFOR: OPTImization in FORestry

■ Publications:

Cao (2003)

Cao et al. (2006)

Cao et al. (2008)

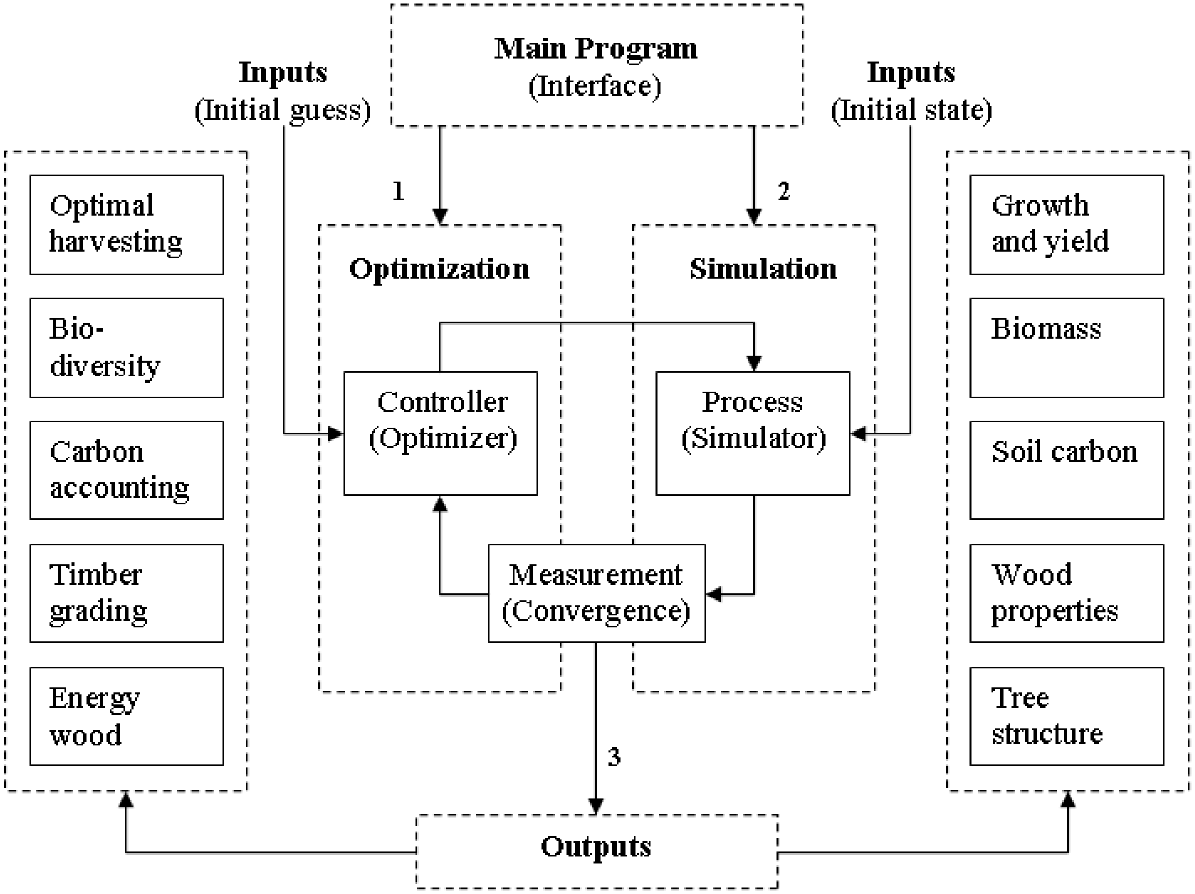
Cao (2010)

Cao et al. (2010)

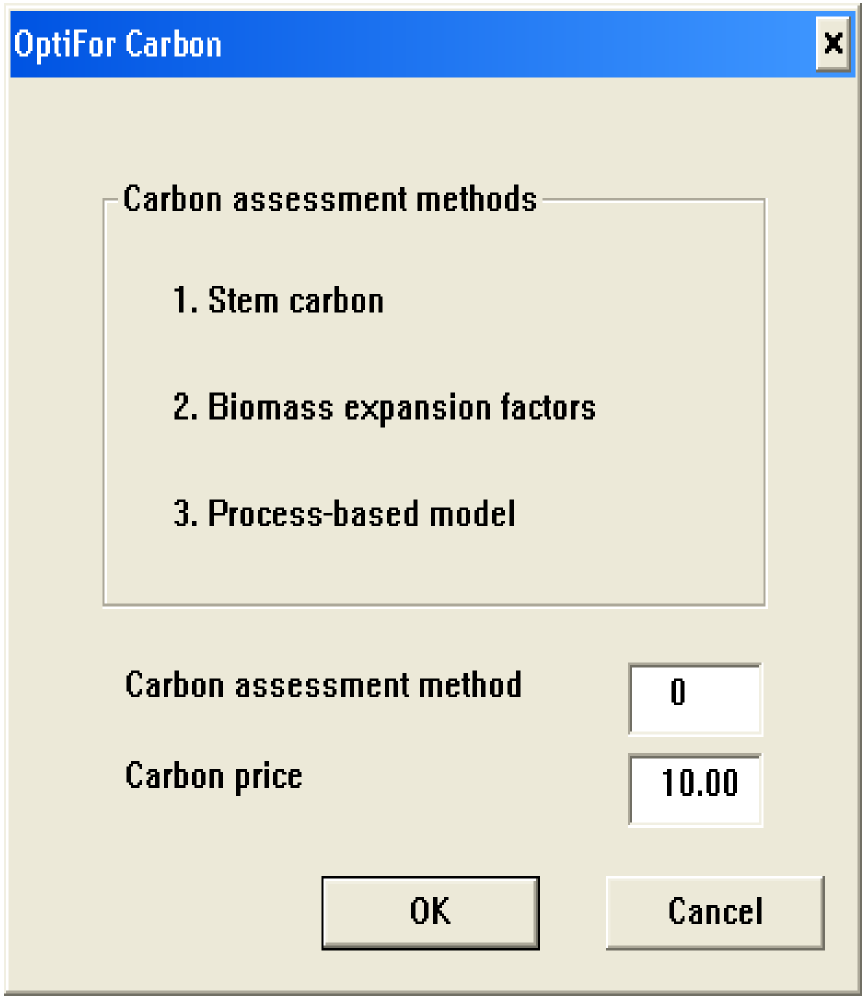
Cao et al. (2015)

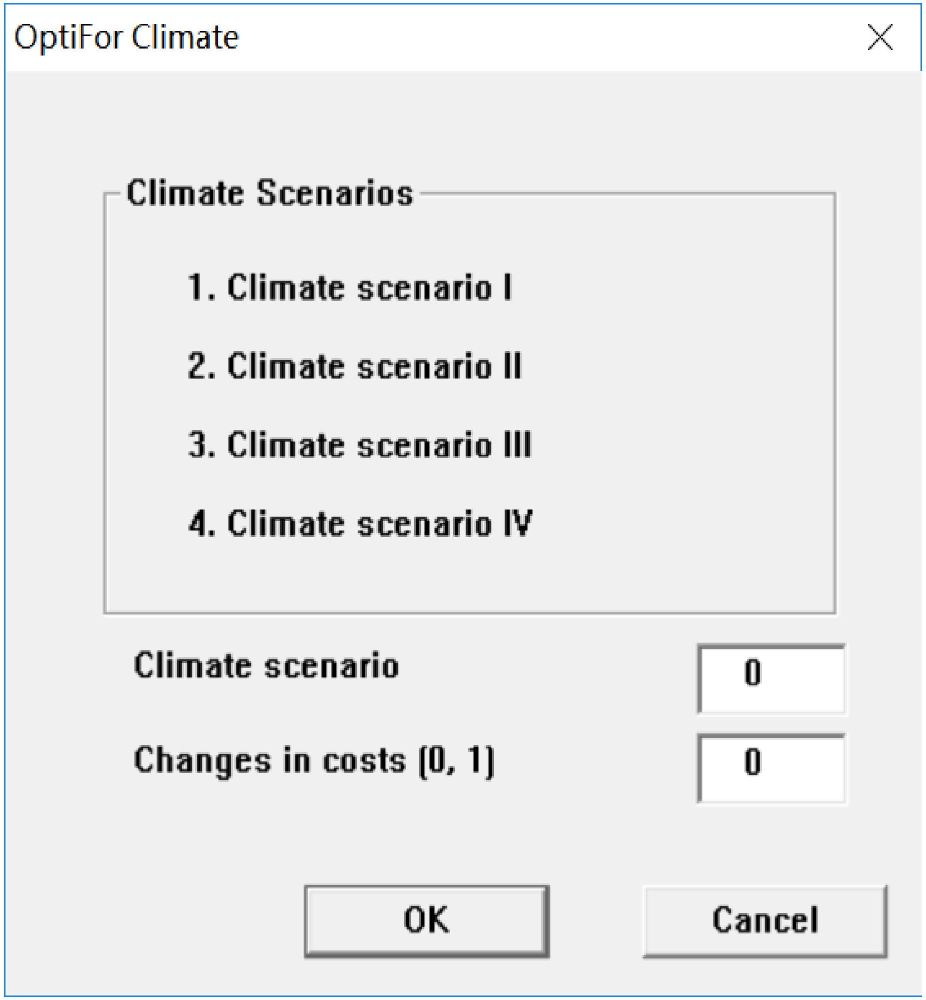
Hurttala et al. (2017)

Xue et al. (2019)

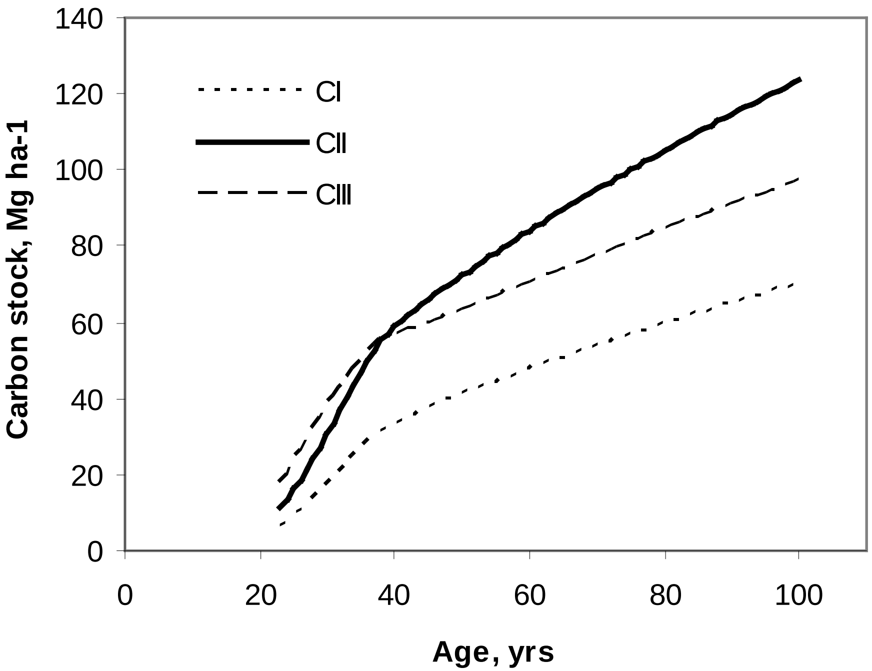


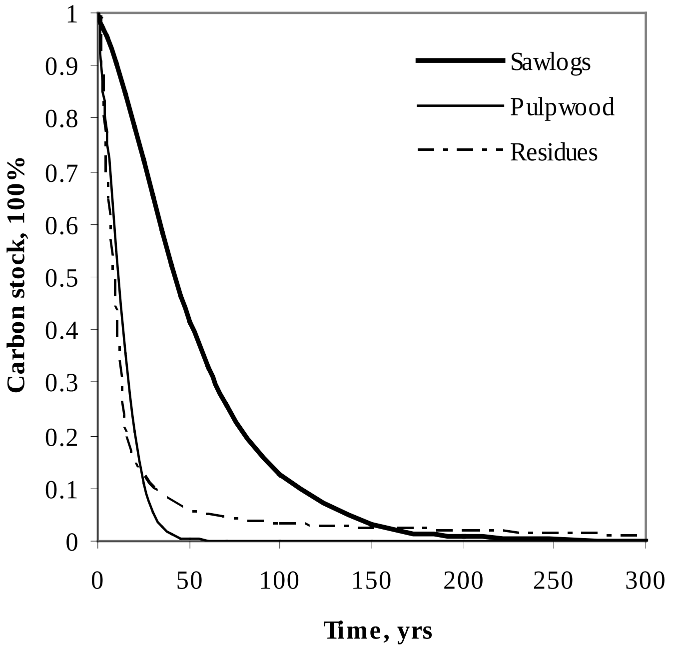
Optimization of Carbon and Climate





Cao et al. (2010)





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OR Techniques

From linear programming, multi-criteria decision-making, to self-learning

Historical notes

- The traditional division in optimization literature was **linear vs. non-linear problems** as the former were thought to be “easier” to solve than the latter.
- The more recent division is between **convex and non-convex problems**, as it has been found that non-linear problems that are convex are often "almost as easy" to solve as linear problems,
- while **non-convex non-linear problems** often pose problems.

Pine-birch forests in NE China

Multi-criteria decision methods

- Multi-Objective Programming (MOP)
- Goal programming (GP)
- Compromise Programming (CP)
- Multi-attribute utility theory (MAUT)
- Fuzzy Mult-Criteria Programming (FMCP)
- Analytic hierarchy process (AHP)
- Other Discrete Methods (ODM)
- Data envelopment analysis (DEA)
- Group Decision Making Techniques (GDM)

Forest Risk Management

Mission Impossible?

Simulated Forest **Real Forest**

Reliability optimization

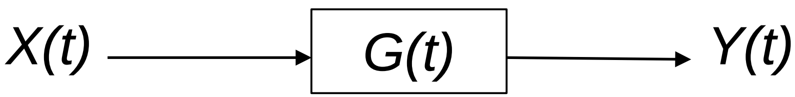
AI algorithms

IUFRO Division 8.03

- 8.03.01 – Torrent, erosion and landslide control
- 8.03.02 – Snow and avalanches
- 8.03.03 – Prevention by watershed management and land-use planning
- 8.03.04 – Disaster documentation and assessment
- 8.03.05 – Forest fires
- 8.03.06 – Impact of wind on forests

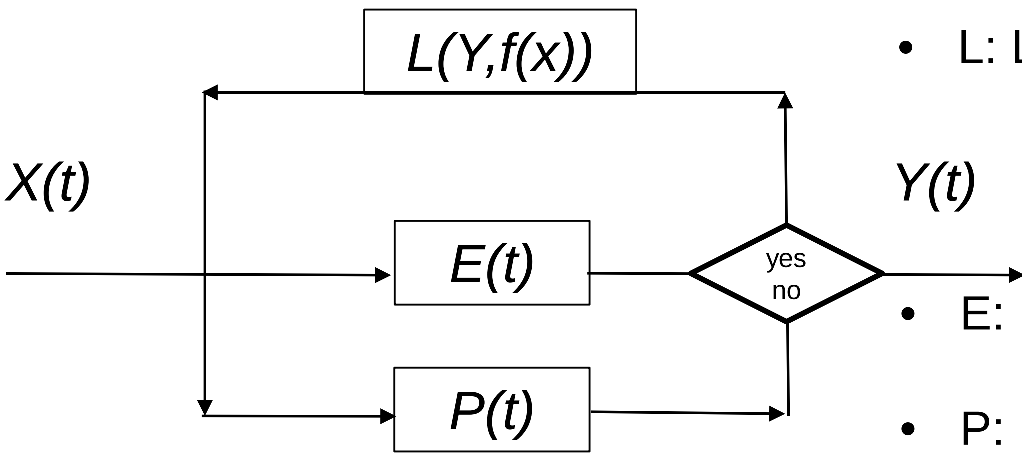
Risk and Uncertainty in Forestry

A multimodal self-learning system



- G, Growth
- t, time

■ deterministic open-loop system



- L: Loss function
- E: Empirical model
- P: Process model

■ parallel closed-loop system

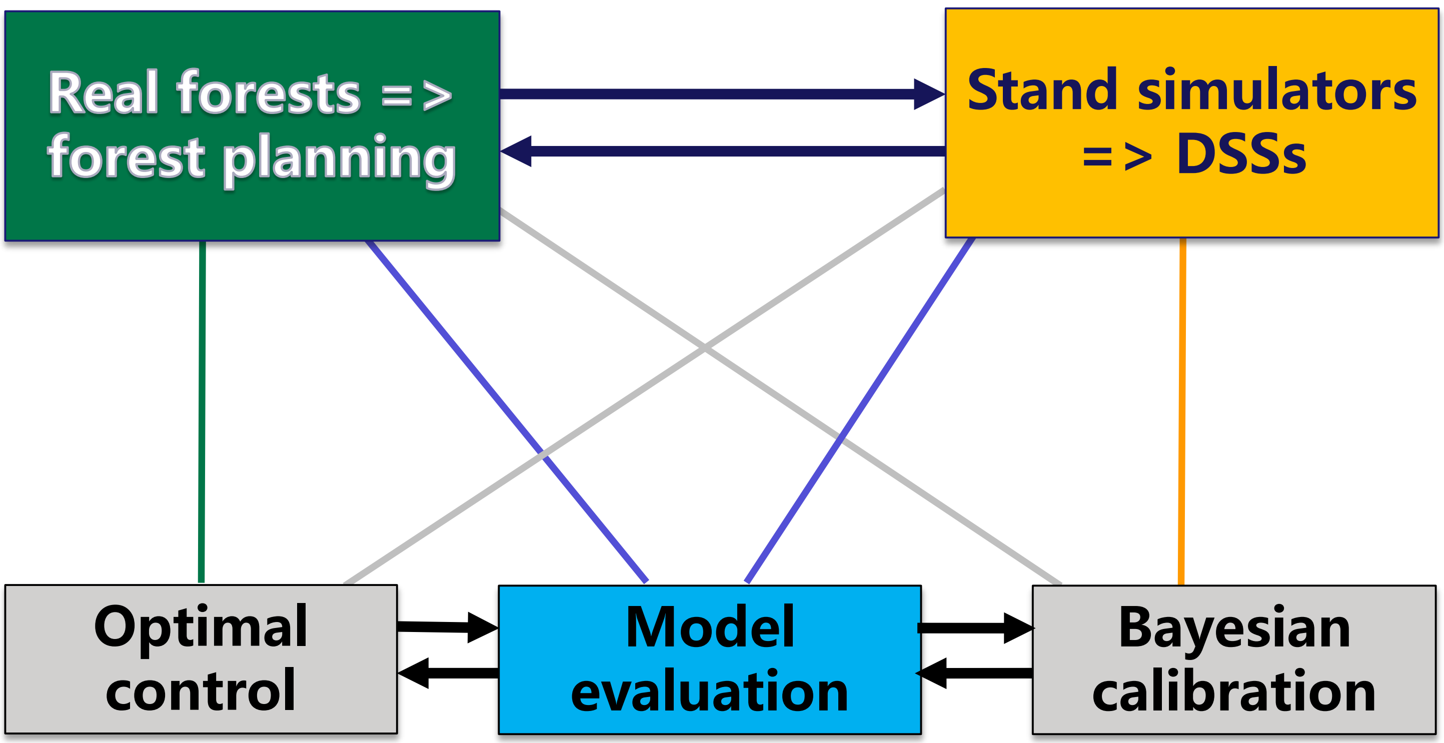
Control of error 冗余控制

- 钱学森 1954. 工程控制论. 麦格劳希尔出版公司. USA

- Reliability by duplication
- Method of multiplexing
- Error in executive component
- Error of multiplexing systems

"This particular method of synthesizing a reliable system out of unreliable elements is called the method of multiplexing by von Neumann." -- 钱学森 Hsue-shen Tsien

Dual closed-loop forest systems



Modified from Wang and Kang (2012)

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OR in Forestry

From observation, prediction, to decision

Systems Analysis, OR, or MS

SSAFR

Symposium on Systems Analysis in Forest Resources

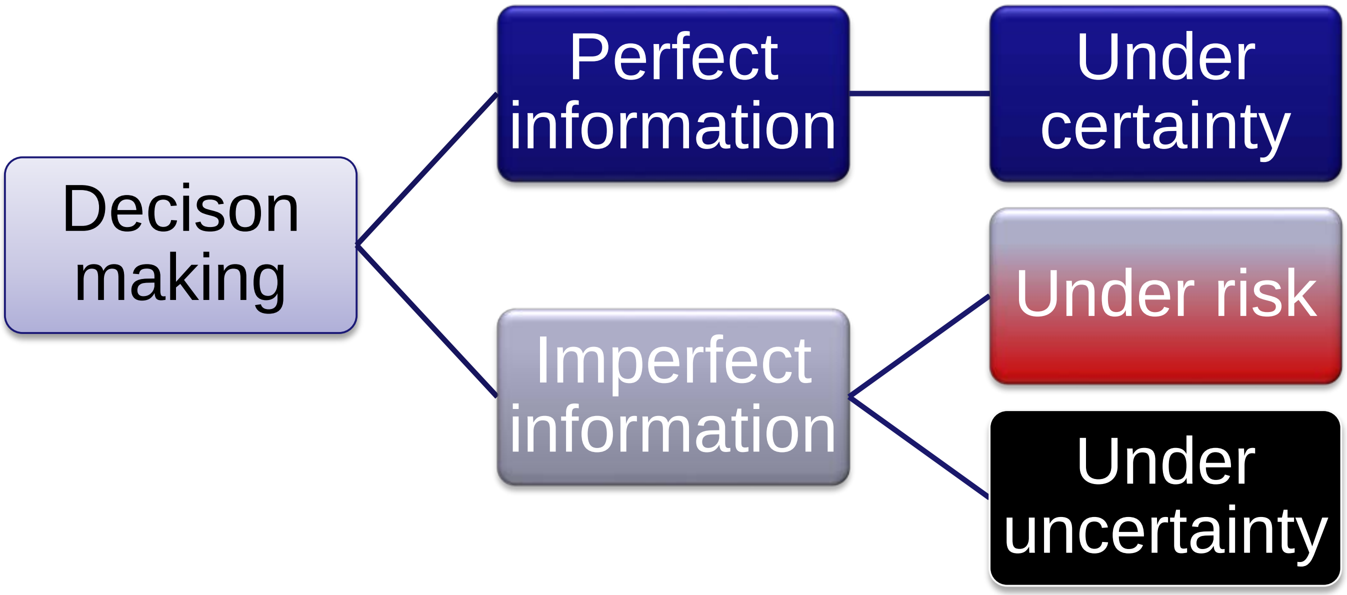
- Since 1975, SSAFR has been the premier international forum for forest systems analysis, operations research (OR), and management science (MS). https://decisions.ctfc.cat/SSAFR2024

SSAFR 2024, Basque, Spain

SSAFR
Symposium on Systems Analysis in Forest Resources

- Application of Remote Sensing In Forestry
- Forest Modelling
- Forest management and planning
- Forest transportation and supply chain optimization
- Wildfire risk simulation, management and decision support
- Forest health, invasive species, and wildlife habitat management
- Spatially explicit optimization
- Stochastic process simulation and optimization
- Quantitative forest and fire economics
- Forest and watershed management
- Data science and machine learning
- Forest systems analysis under the impact of climate change

Decision theory (Taha, 1997)



Committee of SSAFR 2024

SSAFR
Symposium on Systems Analysis in Forest Resources

- Jordi Garcia-Gonzalo (Chair), CTFC, Spain
- Yu Wei, Colorado State University, USA.
- Sándor F. Tóth, University of Washington, USA
- Míriam Piqué i Nicolau, CTFC, Spain
- José C. Borges, Universidade de Lisboa, Portugal
- Mark Finney, USDA Forest Service, USA
- Erin Belval, USDA Forest Service, USA
- David L. Martell, University of Toronto, Ontario, Canada
- Marc McDill, Pennsylvania State University, USA
- Andrés Weintraub P, Universidad de Chile, Chile
- Blas Mola-yudego, University of Eastern Finland, Finland
- Luiz Carlos Estraviz Rodriguez, Departamento de Ciências Florestais ESALQ/USP, Brasil

Strategic, Tactical, or Operational Level

- Strategic forest management
  - *Linear programming*
  - *Scenario analysis*

- Tactical forest management
  - *Spatial optimization*

- Harvest operational models
  - *harvesting,*
  - *transportation,*
  - *log merchandizing*

Applications

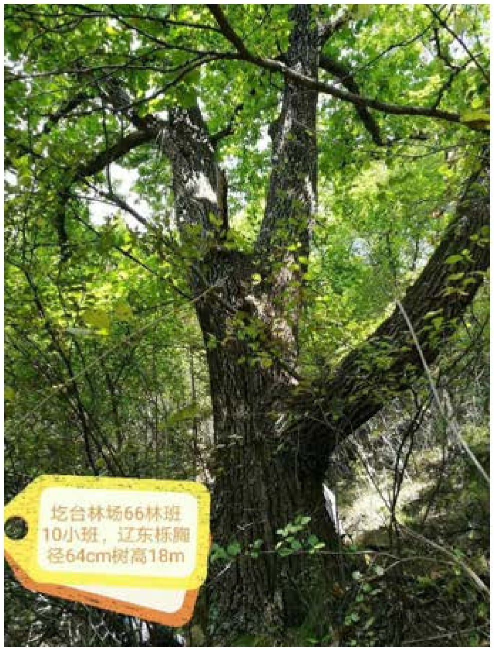
- **Forest policy and economics**
  - *optimal rotation,*
  - *market equilibrium,*
  - *forest valuation,*
  - *MCDM*

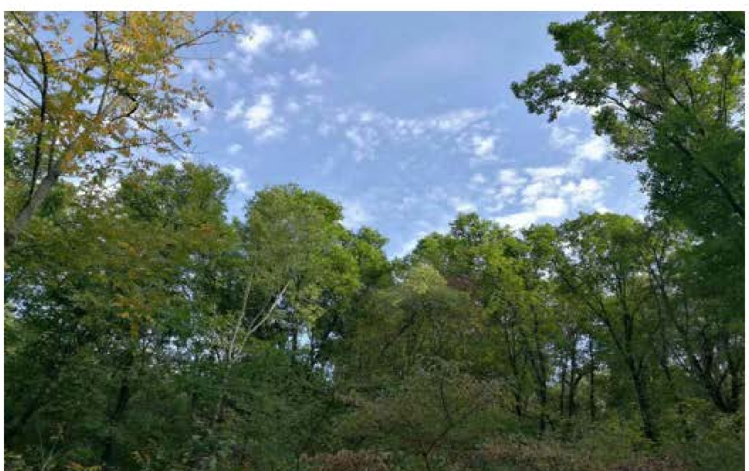
- **Adaptive forest management**
  - *uncertainties of tree growth*
  - *future stochastic prizes,*
  - *adaptive optimization*

A simulation-optimization approach

- USA (e.g., Amidon and Akin, 1968; Brodie et al., 1978; Kao and Brodie, 1979,1980; Roise, 1986; Haight, 1987,1991,1993; Haight and Monserud ,1990; Arthaud and Pelkki ,1996)
- Sweden (e.g., Eriksson 1994,1997; Gong, 1998; Wikström 2000,2001; Lu and Gong, 2003)
- Norway (e.g., Risvand ,1969; Solberg and Haight, 1991; Hoen and Solberg, 1994)
- Denmark (e.g., Thorsen and Helles, 1998; Strange et al., 1999)
- The Netherlands (e.g., Brazee and Bulte, 2000)
- Finland (e.g., Kilkki and Väisänen, 1969; Valsta, 1986,1990,1992; Salminen, 1993; Miina, 1996; Pukkala and Miina, 1997,1998; Hyytiäinen et al., 2003, 2004; Cao et al., 2006; Pukkala, 2009; Cao et al., 2010)

Oak forests in NW China





Forest planning

- 1960s-1980s (e.g. Amidon and Akin 1968, Brodie et al. 1978)
  - Whole-stand models,
  - Linear programming, Dynamic programming
  - Timber production, Optimal rotation, Stocking control
- 1990s-2000s (e.g. Haight and Monserud 1990, Valsta 1992, …)
  - Matrix (size-class) models,
  - Individual-tree models,
  - Non-linear programming, Heuristic algorithms, MCDMs
  - Continues Cover Forest, Environmental concern
- 2010s-present (e.g. Cao et al. 2010, Pukkala et al. 2021)
  - Process-based models,
  - Population-based algorithms, Random forest, Machine learning
  - Multi-functional management

Climate Change Impacts

Does it really matter?

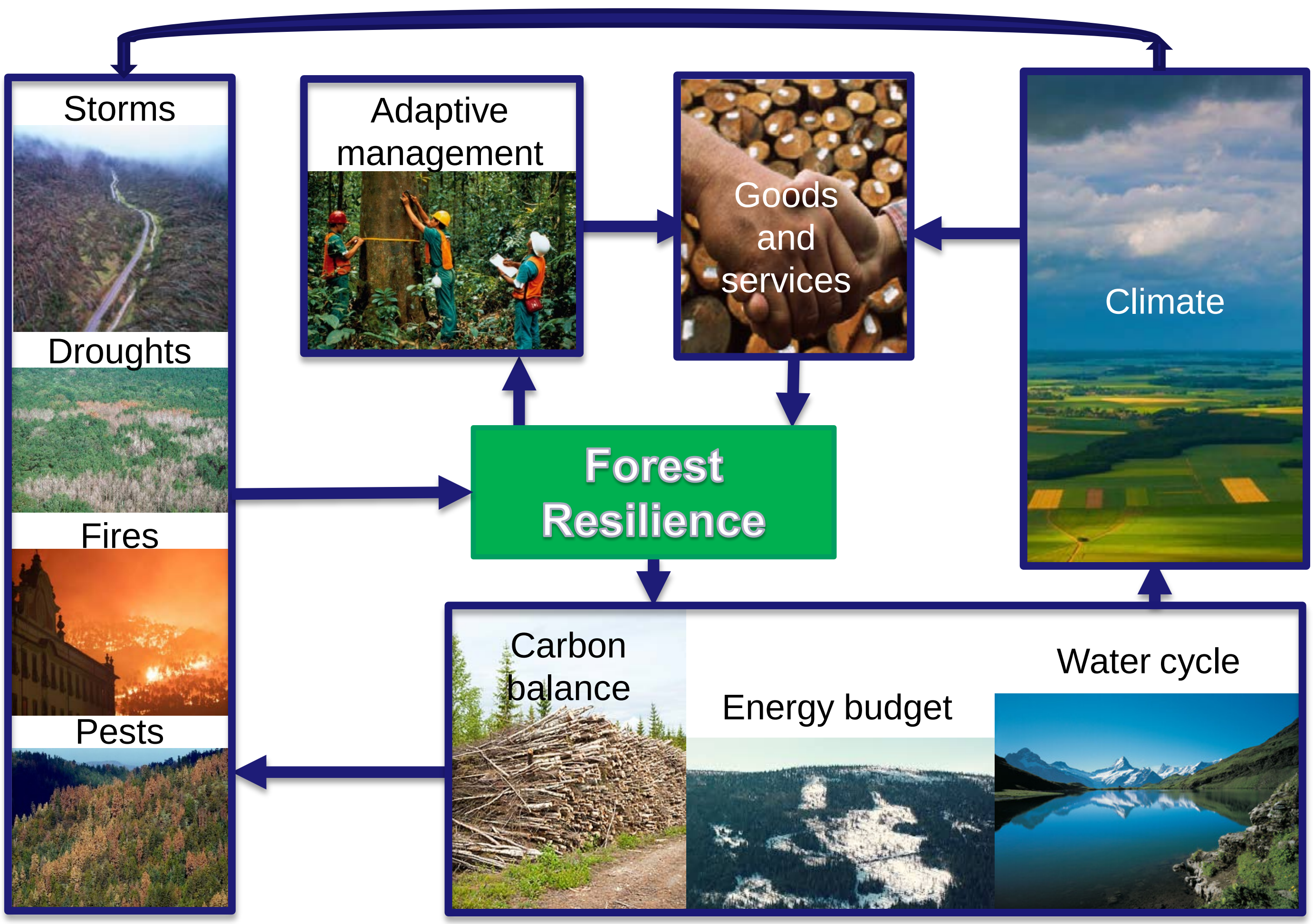
Climate Effects

Process-based models

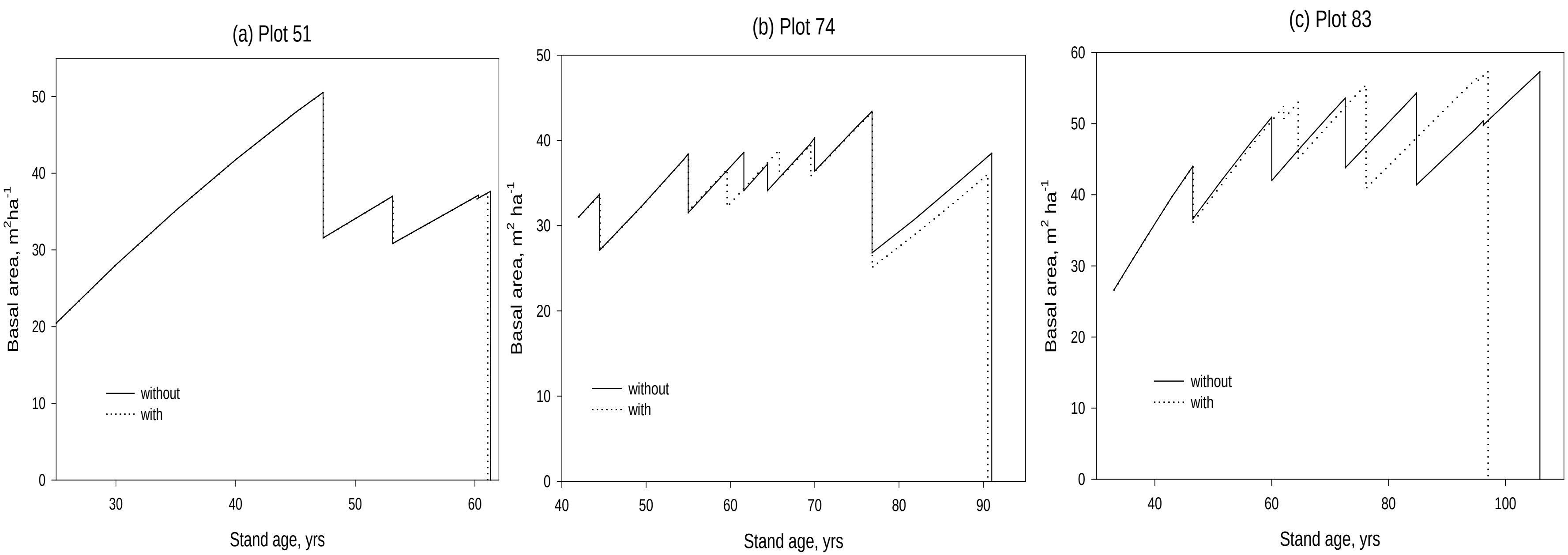
Fires & Pests

AI algorithms

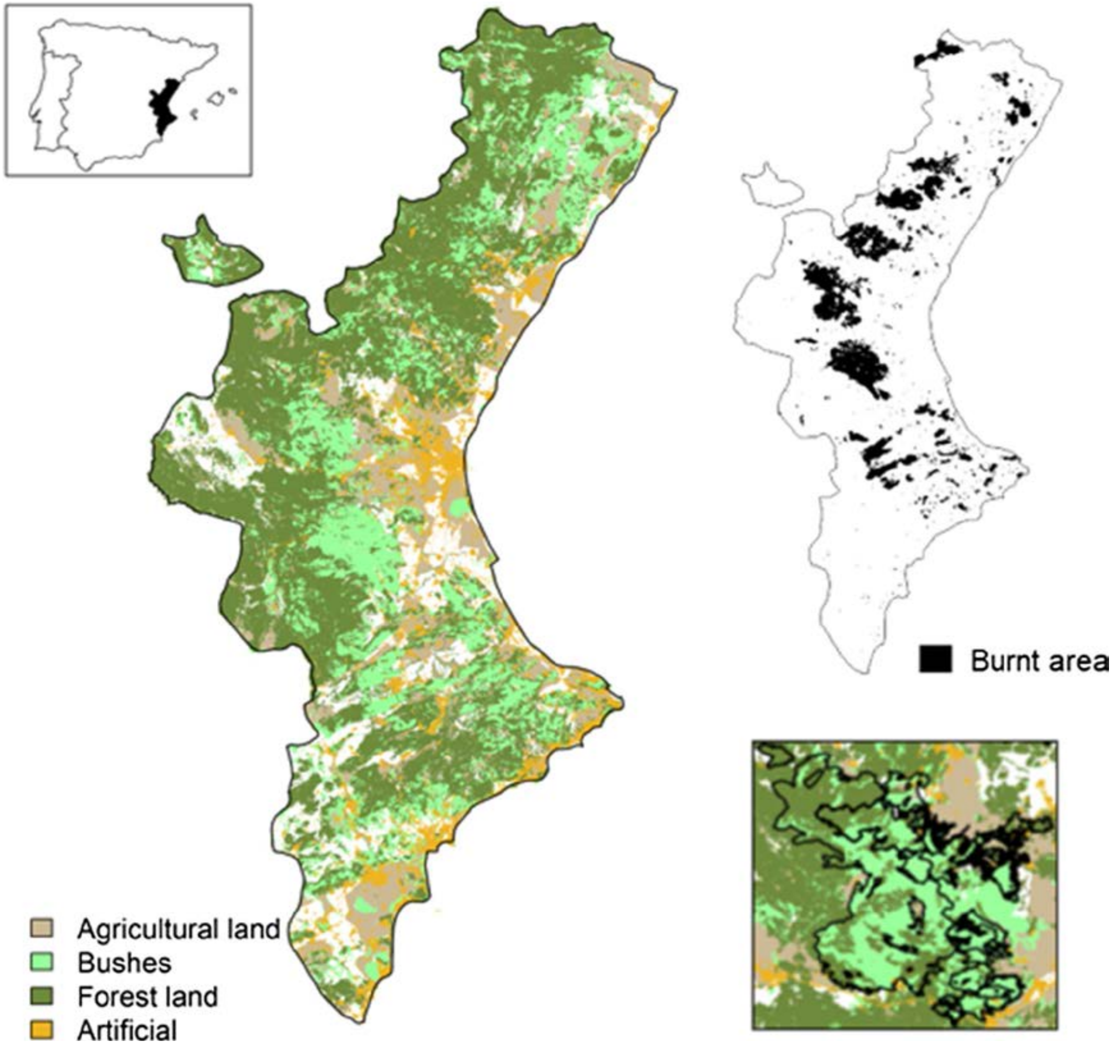
Climate Change and Forest Resilience

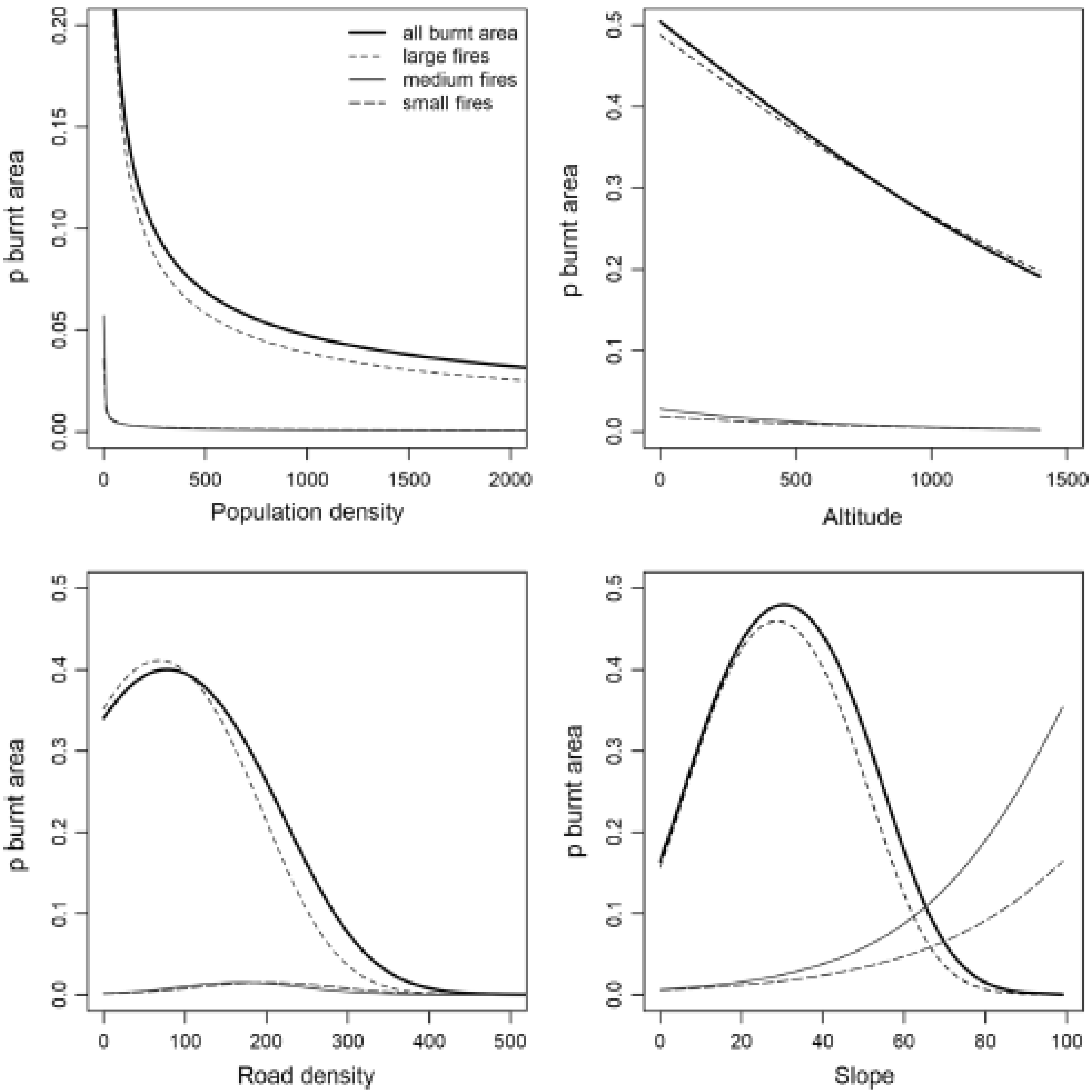


Butt rot effects (Cao 2003)



Fire occurrence in Mediterranean forests





all burnt area
large fires
medium fires
small fires
p burnt area
Population density
Altitude
Road density
Slope
0.00
0.05
0.10
0.15
0.20
0.0
0.1
0.2
0.3
0.4
0.5
0
500
1000
1500
2000
100
200
300
400
20
40
60
80

The Future: Smart Forestry 智慧林业

- Applications 应用场景
  - 智慧生态监测 => 生态价值
  - **数字林木育种 => 经济价值**
  - **智慧林果生产 => 经济价值**
  - **智慧病虫防控 => 经济价值 pests control**
  - **智慧林火管理 => 经济价值 fire management**
  - 虚拟森林漫游 => 社会价值

- The Future 发展方向
  - 大数据 => 大模型 => 大系统
  - 无人化 => 少人化 => 自动化
  - **算源 => 算力 => 算法**

2024 第九届中国林学大会智慧林业分会场

S42 智慧林业创新与应用分会场

分 会 场 主 题：大数据时代的智慧林业技术与应用

分 会 场 主 席：周国模

分会场秘书长：刘金福 孟京辉 董利虎

学术委员会主席：周国模

学术委员会委员：曹田健 王美丽 傅隆生 郭新宇

7 月 27 日（星期六）下午

时 间：13:30-18:00 地 点：西北农林科技大学南校区 S3203 室

内 容：**特邀报告**

主持人：曹田健（西北农林科技大学林学院，教授）

王美丽（西北农林科技大学信息学院，教授）

13:30-14:10 **1. 高清时序数据驱动下的松材线虫病智能防控解决方案**

周国模（浙江农林大学，教授）

14:10-14:50 **2. 考虑不同气候情景下的天然栎类林经营决策支持系统研究**

孟京辉（北京林业大学林学院，教授）

14:50-15:30 **3. 农作物表型大数据获取解析进展**

郭新宇（国家信息化农业工程技术研究中心，研究员）

15:30-15:50 **茶歇/合影**

References

- Bazaraa, M.S., Sherali, H.D. & Shetty, C.M. 1993. Nonlinear Programming: Theory and Algorithms. 2nd Edition. John Wiley & Sons, Inc.
- Bevers, Michael; Barrett, Tara M., tech. comps. 2005. System analysis in forest resources: proceedings of the 2003 symposium. Gen. Tech. Rep. PNW-GTR-656. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 366 p.
- Buongiorno, J. and Gilless, J.K.. 2003. Decision Methods for Forest Resource Management. Academic Press. ISBN 0-12-141360-8.
- Cao, T., 2010. Silvicultural decisions based on simulation-optimization systems. Dissertationes Forestales 103. ISBN 978-951-651-296-2.
- Weintraub, A., Romero, C., Bjorndal, T. (eds.) 2007. Handbook of operations research in natural resources. in the International series in operations research & management science (F. S. Hillier, series editor). Springer. 614 p.

生态仿真优化实验室
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Thank you!

cao@nwafu.edu.cn

第九届中国林学大会智慧林业分会论文集
www.optifor.cn/pdf/S42_2024.pdf