異時点間集約を伴う森林資源管理の離散最適化モデリング

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集約：小規模に区分、管理されてきた林分ユニットに対し、隣接する他のユニットとの統合により、規模を拡大した集約ユニットとして区分を形成・管理

異時点間：時点の異なる期間において、集約ユニットのパターン変化を許容できるように、時間軸を基準としたパターン形成の柔軟化を図る

メリットー＞一度集約されたからと言って、そのパターンを継続する必要はなく、時々の状況に応じて集約ユニットのパターンを変更できる

本研究の目的：時点が異なる期間において、集約ユニットのパターンを生成し、変化できる0-1計画法の枠組みで制約式を考案し、時間軸に対しパターン形成が柔軟な森林資源管理を最適化できる離散最適化モデルを構築

管理目的：伐採から得られる収益の現在価値最大化

1.時間的制約：与えられた森林資源において複数回伐採制約および収穫量制約、**2.空間的制約**：異時点間での最大許容面積内での林分ユニットの集約

1. Temporal harvest scheduling Module (TM): Johnson & Scheurman (1977) *For. Sci.*

Static Treatment Approach: Model I

Decision Variable: a harvest treatment over time
Ex. “Harvest 1st unit at periods 1 and 7”

$x_{ih}=1$ if the h-th treatment is implemented for i-th unit

$$J=\max\sum_{i=1}^{m}\sum_{h=1}^{H}c_{ih}\cdot x_{ih}$$

$$\sum_{h=0}^{H}x_{ih}=1, \qquad \forall i$$
$$(1-\alpha)\cdot v_0\le\sum_{i=1}^{m}\sum_{h=1}^{H}v_{ih}^{t}\cdot x_{ih}\le(1+\alpha)\cdot v_0, \qquad \forall t$$

Table 1: Example of treatments

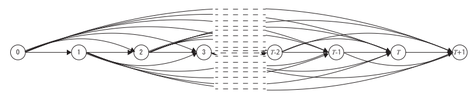
Treatment No.	Decision Variable	Coefficient	Period 1	2	3	4	5	6	7	8	9	10
Treatment	1	$x_{i,1}$	$c_{i,1}$	X	0	0	0	0	0	0	0	0
	2	$x_{i,2}$	$c_{i,2}$	X	0	0	0	0	0	X	0	0
	3	$x_{i,3}$	$c_{i,3}$	X	0	0	0	0	0	0	X	0
	4	$x_{i,4}$	$c_{i,4}$	X	0	0	0	0	0	0	0	X
	5	$x_{i,5}$	$c_{i,5}$	X	0	0	0	0	0	0	0	X
	6	$x_{i,6}$	$c_{i,6}$	0	X	0	0	0	0	0	0	0
	7	$x_{i,7}$	$c_{i,7}$	0	X	0	0	0	0	X	0	0
	8	$x_{i,8}$	$c_{i,8}$	0	X	0	0	0	0	0	X	0
	9	$x_{i,9}$	$c_{i,9}$	0	X	0	0	0	0	0	0	X
	10	$x_{i,10}$	$c_{i,10}$	0	0	X	0	0	0	0	0	0
	11	$x_{i,11}$	$c_{i,11}$	0	0	X	0	0	0	0	X	0
	12	$x_{i,12}$	$c_{i,12}$	0	0	X	0	0	0	0	0	X
	13	$x_{i,13}$	$c_{i,13}$	0	0	0	X	0	0	0	0	0
	14	$x_{i,14}$	$c_{i,14}$	0	0	0	X	0	0	0	0	X
	15	$x_{i,15}$	$c_{i,15}$	0	0	0	0	X	0	0	0	0
	16	$x_{i,16}$	$c_{i,16}$	0	0	0	0	0	X	0	0	0
	17	$x_{i,17}$	$c_{i,17}$	0	0	0	0	0	0	X	0	0
	18	$x_{i,18}$	$c_{i,18}$	0	0	0	0	0	0	0	X	0
	19	$x_{i,19}$	$c_{i,19}$	0	0	0	0	0	0	0	0	X
	20	$x_{i,20}$	$c_{i,20}$	0	0	0	0	0	0	0	0	X

Note: X denotes harvesting while 0 denotes no harvesting

Dynamic Treatment Approach: Model II

Decision Variable: a harvest at each period
Ex. “Harvest 1st unit at period 1”

$x_{st}^{i}=1$ if the i-th unit is harvested at stage t (period t) after replanting at stage s ($0<s+k<t$) or from the current stage 0 ($s=0$) as the first harvest, given the minimum rotation period or stage by k



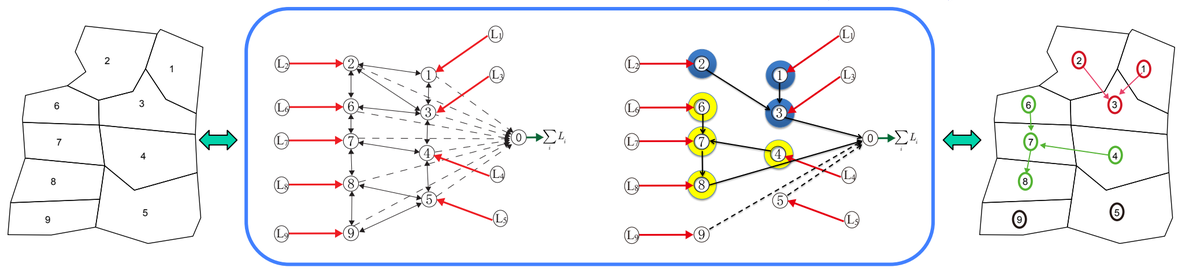
Dynamic network for harvests over time

$$J=\max\sum_{i=1}^{m}\sum_{t=1}^{T+1}\sum_{s=0}^{\max(0,t-k)}c_{st}^{i}\cdot x_{st}^{i}$$

$$\sum_{\tau=0}^{\max(0,s-k)}x_{\tau s}^{i}=\sum_{t=\min(s+k,T+1)}^{T+1}x_{st}^{i}, \quad \forall i,s=1,\ldots,T$$
$$\sum_{t=1}^{T+1}x_{0t}^{i}=1, \qquad \forall i$$
$$y_{ij}^{B(n+1)}\le\sum_{k\in(\mathbb{MB}_i\cap\mathbb{MB}_j)}u_{ijk}^{(n)}, \qquad \forall j\in\mathbb{MB}_i,\forall i,n=1,\ldots,N$$

2. Spatial component Module (SM): Yoshimoto & Asante (2018) *For. Sci.*

Maximum Flow Constraints (MFC)

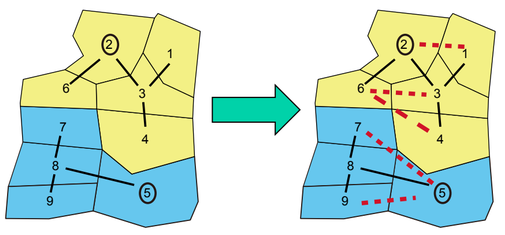


$y_{ij}=1$ if an arc is connected between i-th and j-th node
$w_{i,j}$: flow from i- to j-th node
L_i : area flow from i-th node
L^{up} : maximum size for a cluster
$\mathbb{NB}_i$: a set of units adjacent to i-th unit over common boarder

$$y_{ij}+y_{ji}\le 1, \quad \forall j\in\mathbb{NB}_i,\forall i$$
$$y_{i0}+\sum_{j\in\mathbb{NB}_i}y_{ij}=1, \qquad \forall i$$
$$w_{ij}\le L^{up}\cdot y_{ij}, \quad \forall j\in\mathbb{NB}_i,\forall i$$

$$w_{i0}+\sum_{j\in\mathbb{NB}_i}w_{ij}=\sum_{j\in\mathbb{NB}_i}w_{ji}+L_i, \ \forall i$$
$$\sum_{i=1}^{m}w_{i0}=\bar{L}$$
$$w_{i0}\le L^{up}\cdot y_{i0}, \ \forall i\in\mathbb{C}$$

Sequential Triangle Connection (STC)



$y_{ij}^{B(n)}=1$ if connecting arc from i-th to j-th units adjacent over common boarder and edge at n-th ordered process
$u_{ijk}^{(n)}=1$ if forming a triangle among i-, j- and k-th units adjacent over common boarder and edge at n-th ordered process
$\mathbb{MB}_i$: a set of units adjacent to i-th unit over common boundary and edge
N: the maximum number of STC processes

$$y_{ij}^{B(1)}=y_{ij}+y_{ji}, \qquad \forall j\in\mathbb{NB}_i,\forall i$$
$$2\cdot u_{ijk}^{(n)}+3\cdot\sum_{l=1}^{n-1}u_{ijk}^{(l)}\le\sum_{l=1}^{n}\{y_{ij}^{B(l)}+y_{ik}^{B(l)}+y_{jk}^{B(l)}\}\le 2\cdot u_{ijk}^{(n)}+3\cdot\sum_{l=1}^{n-1}u_{ijk}^{(l)}+1, \qquad \forall k\in(\mathbb{MB}_i\cap\mathbb{MB}_j),\forall j\in\mathbb{MB}_i,\forall i,n=1,\ldots,N-1$$
$$3\cdot u_{ijk}^{(n)}\le\sum_{l=1}^{n+1}\{y_{ij}^{B(l)}+y_{ik}^{B(l)}+y_{jk}^{B(l)}\}, \qquad \forall k\in(\mathbb{MB}_i\cap\mathbb{MB}_j),\forall j\in\mathbb{MB}_i,\forall i,n=1,\ldots,N-1$$
$$y_{ij}^{B(n+1)}\le\sum_{k\in(\mathbb{MB}_i\cap\mathbb{MB}_j)}u_{ijk}^{(n)}, \qquad \forall j\in\mathbb{MB}_i,\forall i,n=1,\ldots,N-1$$
$$\sum_{n=1}^{N}y_{ij}^{B(n)}\le 1, \quad \forall j\in\mathbb{MB}_i,\forall i$$

3. Linkage Module (LM)

Linking decision variables of TM and SM

MF-Model I (by Y-A)

$z_{ij}^{h}=x_{ih}\cdot x_{jh}$ **Same treatment**

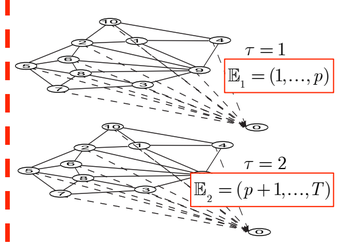
$$2\cdot z_{ij}^{h}\le x_{ih}+x_{jh}\le 2\cdot z_{ij}^{h}+1, \quad \forall j\in\mathbb{NB}_i,\forall i,\forall h(\neq 0)$$
$$a_{hl}^{v}\cdot x_{ih}+a_{lh}^{v}\cdot x_{jl}\le 1, \quad \forall j\in\mathbb{NB}_i,\forall i,\forall l(\neq h),\forall h$$
$$\sum_{n=1}^{N}y_{ij}^{B(n)}=\sum_{h=1}^{H}z_{ij}^{h}, \qquad \forall j\in\mathbb{NB}_i,\forall i$$

MF-Model II

$z_{ij}^{t}=\left(\sum_{s=0}^{\max(0,t-k)}x_{st}^{i}\right)\cdot\left(\sum_{s=0}^{\max(0,t-k)}x_{st}^{j}\right)$ **Concurrent harvest**

$$2\cdot z_{ij}^{t}\le\sum_{s=0}^{\max(0,t-k)}(x_{st}^{i}+x_{st}^{j})\le 2\cdot z_{ij}^{t}+1, \ \forall j\in\mathbb{NB}_i,\forall i,\forall t$$
$$\sum_{s=0}^{\max(0,t-k)}x_{st}^{i}+\sum_{p=t+1}^{(t+g-1)}\sum_{s=0}^{\max(0,t+g-1-k)}x_{sp}^{j}\le 1, \ \forall j\in\mathbb{NB}_i,\forall i,\forall t$$
$$\sum_{n=1}^{N}y_{ij}^{B(n)}\le\sum_{t=1}^{T}z_{ij}^{t}\le K^{\max}\cdot\sum_{n=1}^{N}y_{ij}^{B(n)}, \quad \forall j\in\mathbb{NB}_i,\forall i,\forall t$$

4. Inter-Temporal Aggregation



$\tau=1$
$\mathbb{E}_1=(1,\ldots,p)$
$\tau=2$
$\mathbb{E}_2=(p+1,\ldots,T)$

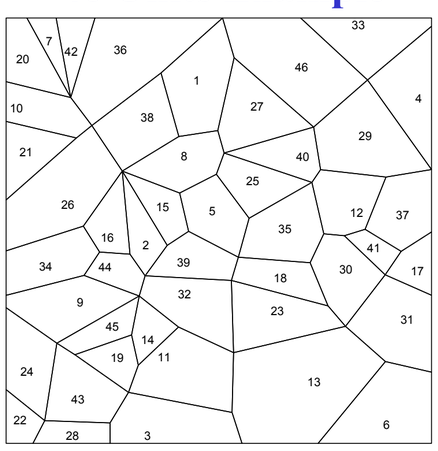
Multilayers for inter-temporal aggregation by $\tau=(1,2)$

$$y_{ij}^{\tau}+y_{ji}^{\tau}\le 1, \quad \forall j\in\mathbb{NB}_i,\forall i,\forall\tau$$
$$y_{i0}^{\tau}+\sum_{j\in\mathbb{NB}_i}y_{ij}^{\tau}=1, \qquad \forall i,\forall\tau$$
$$w_{ij}^{\tau}\le L^{up}\cdot y_{ij}^{\tau}, \quad \forall j\in\mathbb{NB}_i,\forall i,\forall\tau$$
$$w_{i0}^{\tau}+\sum_{j\in\mathbb{NB}_i}w_{ij}^{\tau}=\sum_{j\in\mathbb{NB}_i}w_{ji}^{\tau}+L_i, \ \forall i,\forall\tau$$
$$\sum_{i=1}^{m}w_{i0}^{\tau}=\bar{L}, \qquad \forall\tau$$
$$w_{i0}^{\tau}\le L^{up}\cdot y_{i0}^{\tau}, \ \forall i\in\mathbb{C},\forall\tau$$
$$y_{ij}^{\tau B(1)}=y_{ij}^{\tau}+y_{ji}^{\tau}, \qquad \forall j\in\mathbb{NB}_i,\forall i,\forall\tau$$

$$2\cdot u_{ijk}^{\tau(n)}+3\cdot\sum_{l=1}^{n-1}u_{ijk}^{\tau(l)}\le\sum_{l=1}^{n}\{y_{ij}^{\tau B(l)}+y_{ik}^{\tau B(l)}+y_{jk}^{\tau B(l)}\}\le 2\cdot u_{ijk}^{\tau(n)}+3\cdot\sum_{l=1}^{n-1}u_{ijk}^{\tau(l)}+1,$$
$$\forall k\in(\mathbb{MB}_i\cap\mathbb{MB}_j),\forall j\in\mathbb{MB}_i,\forall i,n=1,\ldots,N-1,\forall\tau$$
$$3\cdot u_{ijk}^{\tau(n)}\le\sum_{l=1}^{n+1}\{y_{ij}^{\tau B(l)}+y_{ik}^{\tau B(l)}+y_{jk}^{\tau B(l)}\},$$
$$\forall k\in(\mathbb{MB}_i\cap\mathbb{MB}_j),\forall j\in\mathbb{MB}_i,\forall i,n=1,\ldots N-1,\forall\tau$$
$$y_{ij}^{\tau B(n+1)}\le\sum_{k\in(\mathbb{MB}_i\cap\mathbb{MB}_j)}u_{ijk}^{\tau(n)}, \qquad \forall j\in\mathbb{MB}_i,\forall i,n=1,\ldots N-1,\forall\tau$$
$$\sum_{n=1}^{N}y_{ij}^{\tau B(n)}\le 1, \quad \forall j\in\mathbb{MB}_i,\forall i,\forall\tau$$
$$\sum_{n=1}^{N}y_{ij}^{\tau B(n)}\le\sum_{t=1}^{T}z_{ij}^{t}\le K^{\max}\cdot\sum_{n=1}^{N}y_{ij}^{\tau B(n)}, \ \forall j\in\mathbb{NB}_i,\forall i,\forall t\in\mathbb{E}_\tau,\forall\tau$$

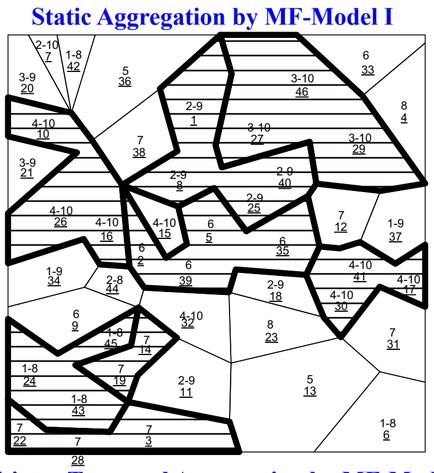
結果

46 Units Example

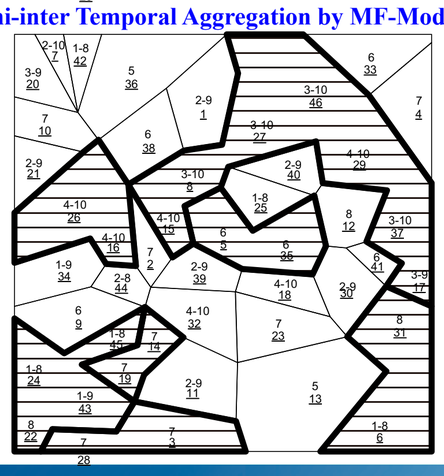


Max cluster size:50ha
Planning periods: 10 (x5yrs)
Minimum rotation: 6 periods
Price: unit price per volume
Discount rate: 3%
# of Duration: 2 (1~5, 6~10)

Static Aggregation by MF-Model I



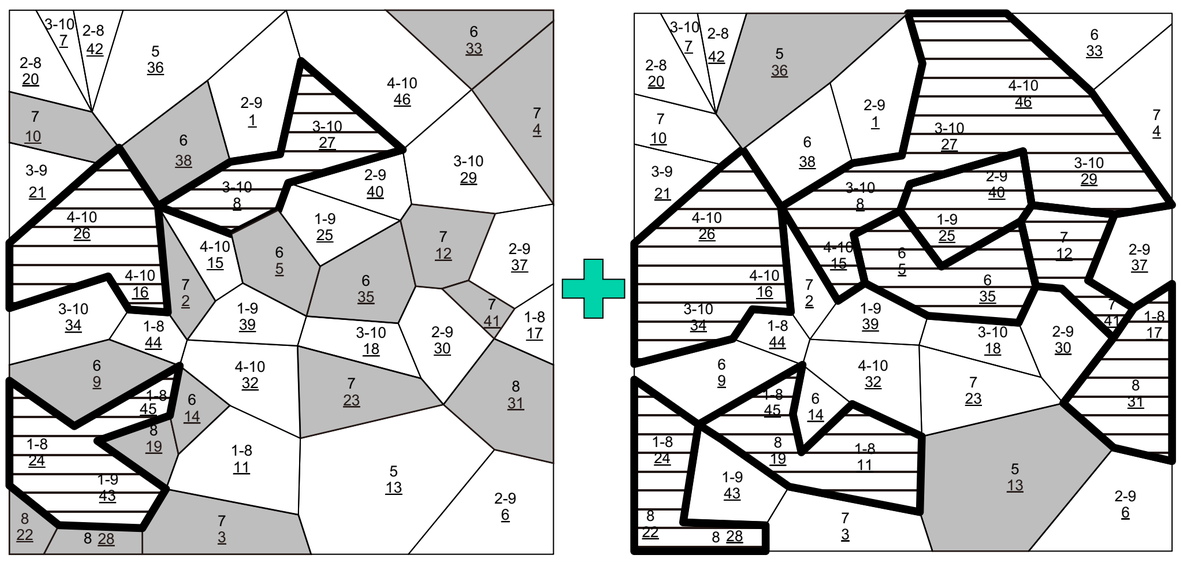
Semi-inter Temporal Aggregation by MF-Model II



Inter-Temporal Aggregation by MF-Model II over 2 Durations

1) Aggregation from 1st to 5th period
$\tau=1,\ \mathbb{E}_1=(1,\ldots,5)$

2) Aggregation from 6th to 10th period
$\tau=2,\ \mathbb{E}_1=(6,\ldots,10)$



Notes:
1. The underlined number indicates ID of forest units.
2. Two numbers connected by “-“ indicate the period of the first harvest and the second.
3. The single number indicates single harvest period.
4. Grey polygons are not harvested in the corresponding duration.
5. The bared polygon indicates clusters.