Estimating SOC Change for summerfallow reduction in Canada

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Agriculture and Agri-Food Canada   Agriculture et Agroalimentaire Canada

Canada

Canada – Land Use, Land-Use Change and Forestry (LULUCF) Accounting

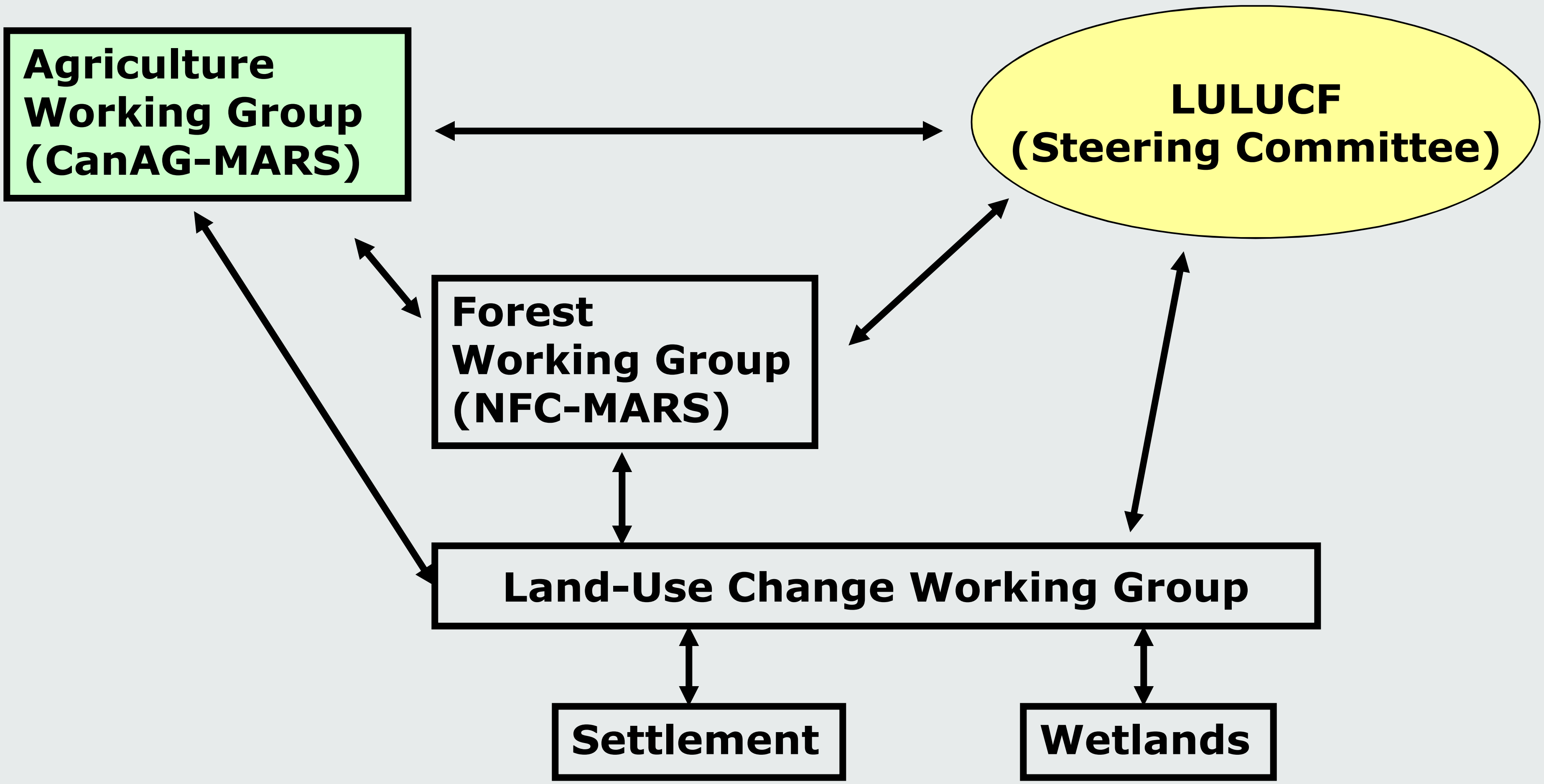
- United Nations Framework Convention on Climate Change
  - All greenhouse gas (GHG) sources and removals
  - Includes LULUCF
- Kyoto Protocol
  - Like Convention except, for LULUCF, only elected activity of cropland management and mandatory activity of afforestation, reforestation, and deforestation.
  - **Cropland Management:** *...is the system of practices on land on which agricultural crops are grown and on land that is set aside or temporarily not being used for crop production.*

Canada and UNFCCC and Kyoto Protocol Reporting

- Canadian implemented LULUCF Working Groups
  - Agriculture Working Group [Environment Canada (EC) and Agriculture and Agri-Food Canada (AAFC)]
  - Forestry Working Group [EC and Natural Resources Canada – Canada Forest Service (NRCan-CFS)]
  - Land Use Change Subgroup (EC, AAFC, and NRCan-CFS)

Structure of the Integrated Canadian Government Greenhouse-Gas Land Inventory

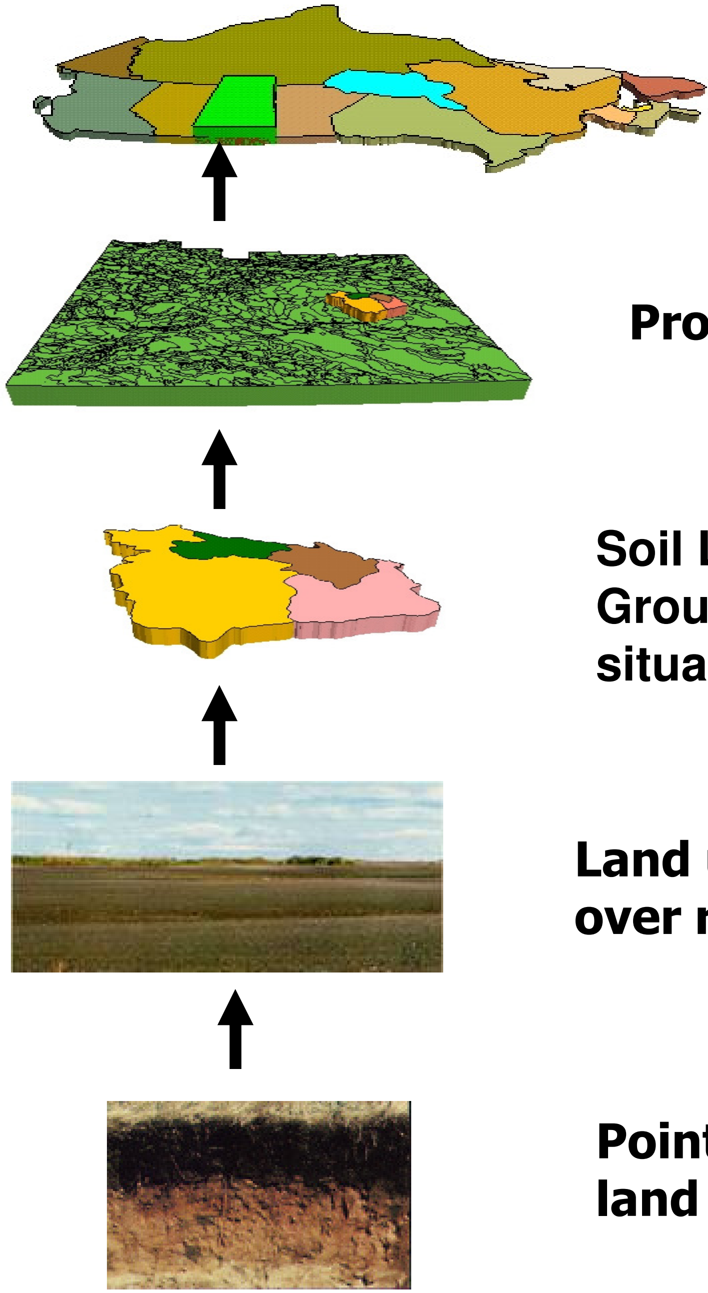
(Land Use, Land-Use Change, and Forestry Monitoring, Accounting, and Reporting System)



Canadian Agricultural Greenhouse Gas – Monitoring Accounting and Reporting System (CanAG-MARS)

- Based on relational database of land (soil) and associated cropland and grazing land management
  - Areas and location of activities causing C change
- For Land Use, Land-Use Change and Forestry (LULUCF) C change factors applied to activities to calculate soil C change
  - Factors come from modelling of C dynamics or from combination of modelling and results of empirical studies.

Bottom-Up Approach



Canada

Province, region, or reporting unit

Soil Landscapes of Canada (SLC) polygons: Group of spatially related land use-management situations

Land use-management : related point estimates over range of soils

Point estimate of C change for a specific soil-land use-management situation

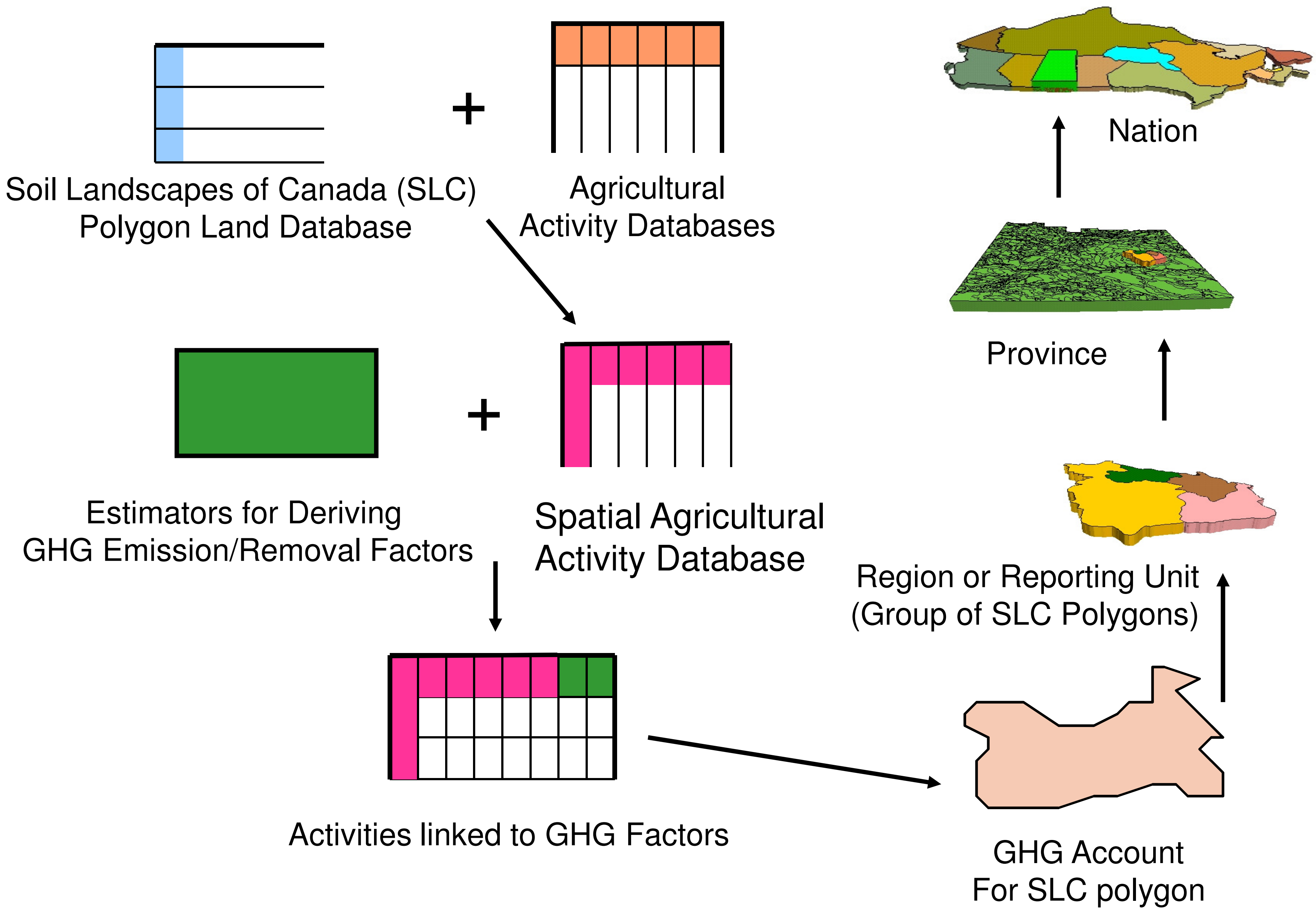
Basic C Accounting Method

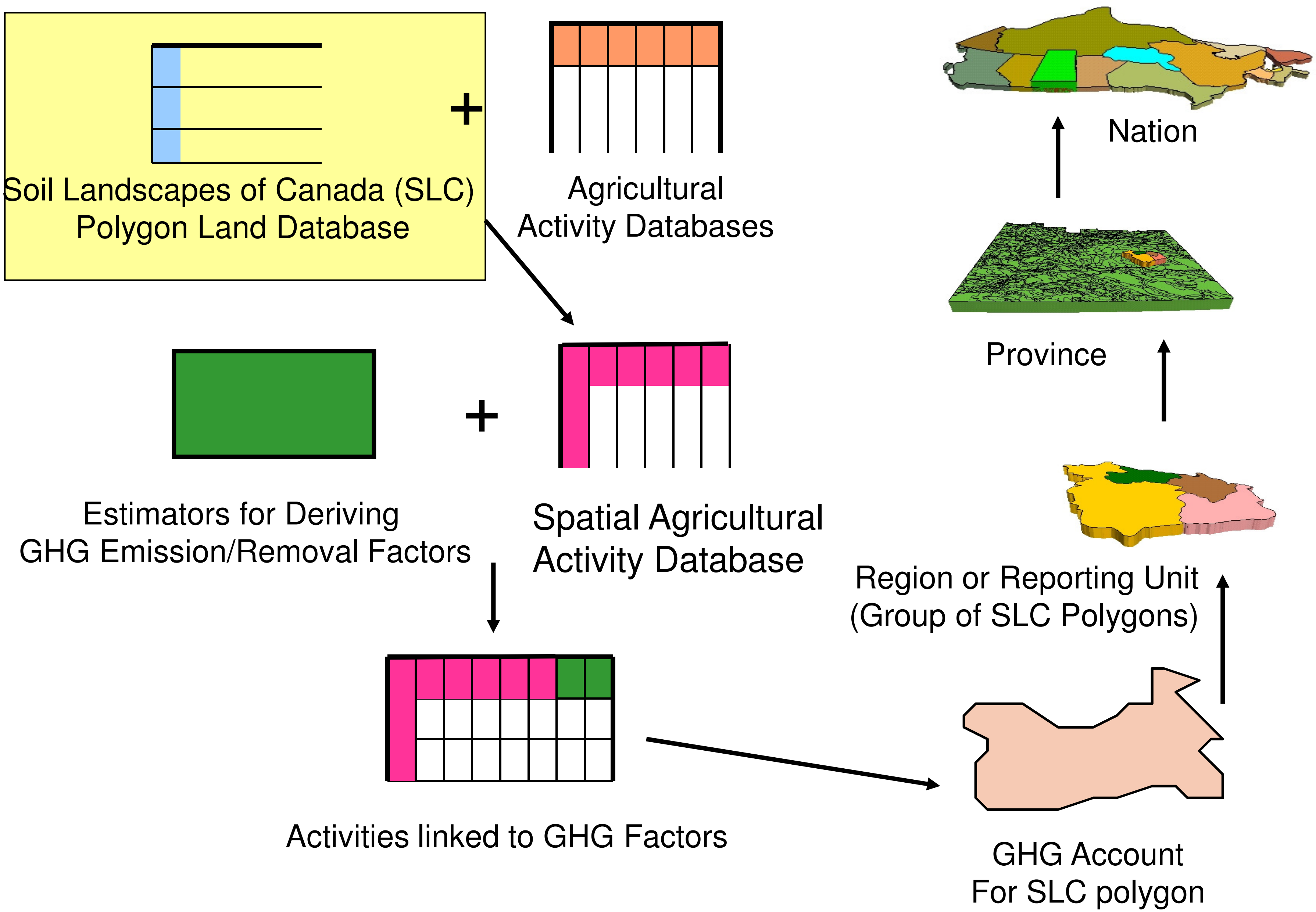
- ***Annual C stock change = Activity*** x ***Factor***
- ***Annual C stock change*** includes that in
  - above- and below-ground biomass (plants)
  - above- and below-ground dead organic matter (identifiable plant or animal residues)
  - soil organic C (below ground organic C that is not biomass or dead organic matter)
- ***Activity*** is the amount of a specific land-use or management change (LUMC) that produces change in C stocks
  - Examples: reduction in summerfallow frequency, clearing trees to increase agricultural land
- ***Factor*** is a coefficient of change in C stocks per unit of the activity
  - IPCC exclusively uses the term Factor for coefficient
- This method versatile, transparent, comparable, and flexible
  - As activity data and/or scientific data improves, more specific factors can be derived

C change in practice

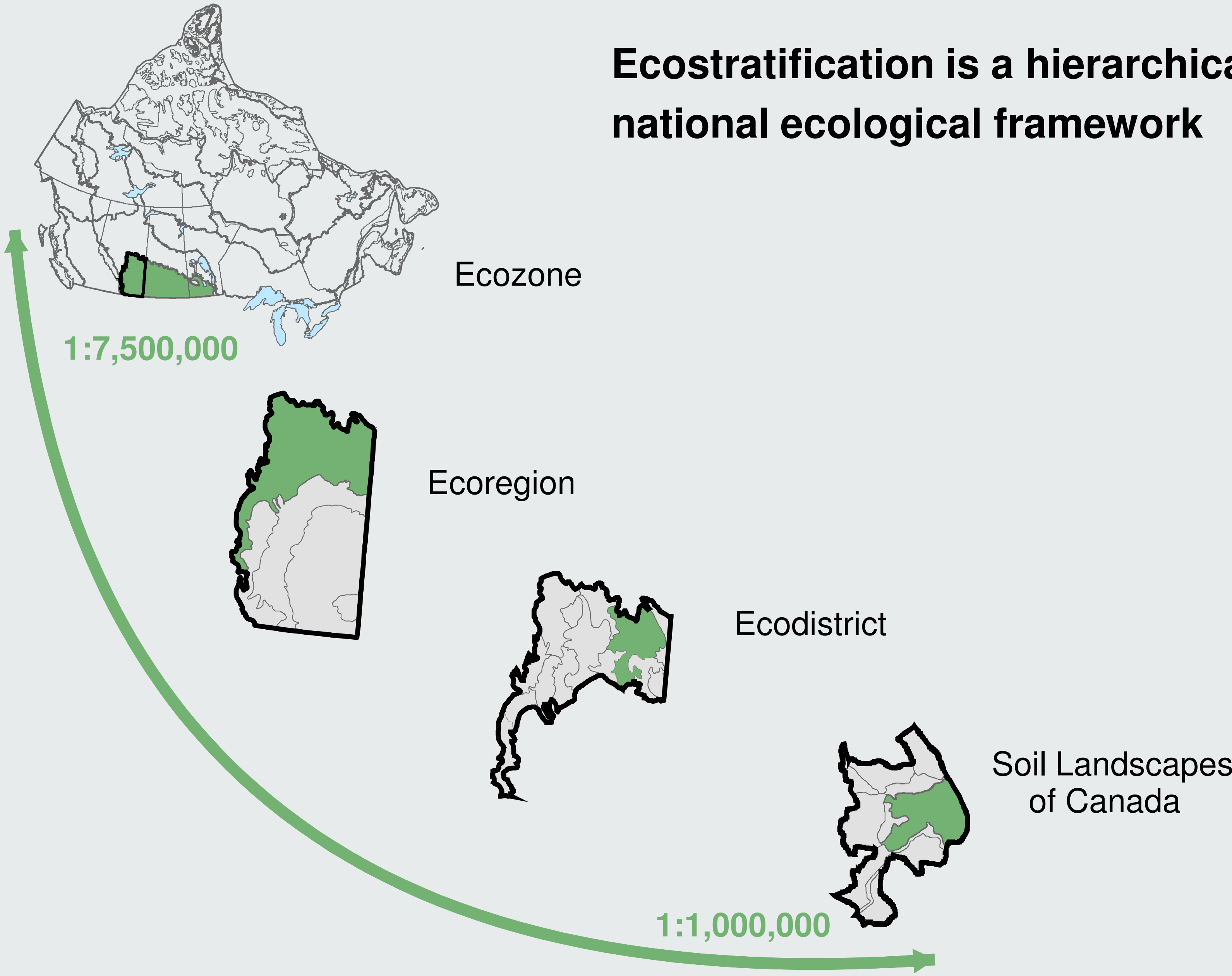
- C change for agricultural land only estimated for those soil-land use-management situations known to significantly affect C balance
  - Change in summerfallow area
  - Change in area under different tillage systems
  - Change in area of perennial vegetation
  - Deforestation to agriculture
  - Grassland to Cropland conversions

System Schematic



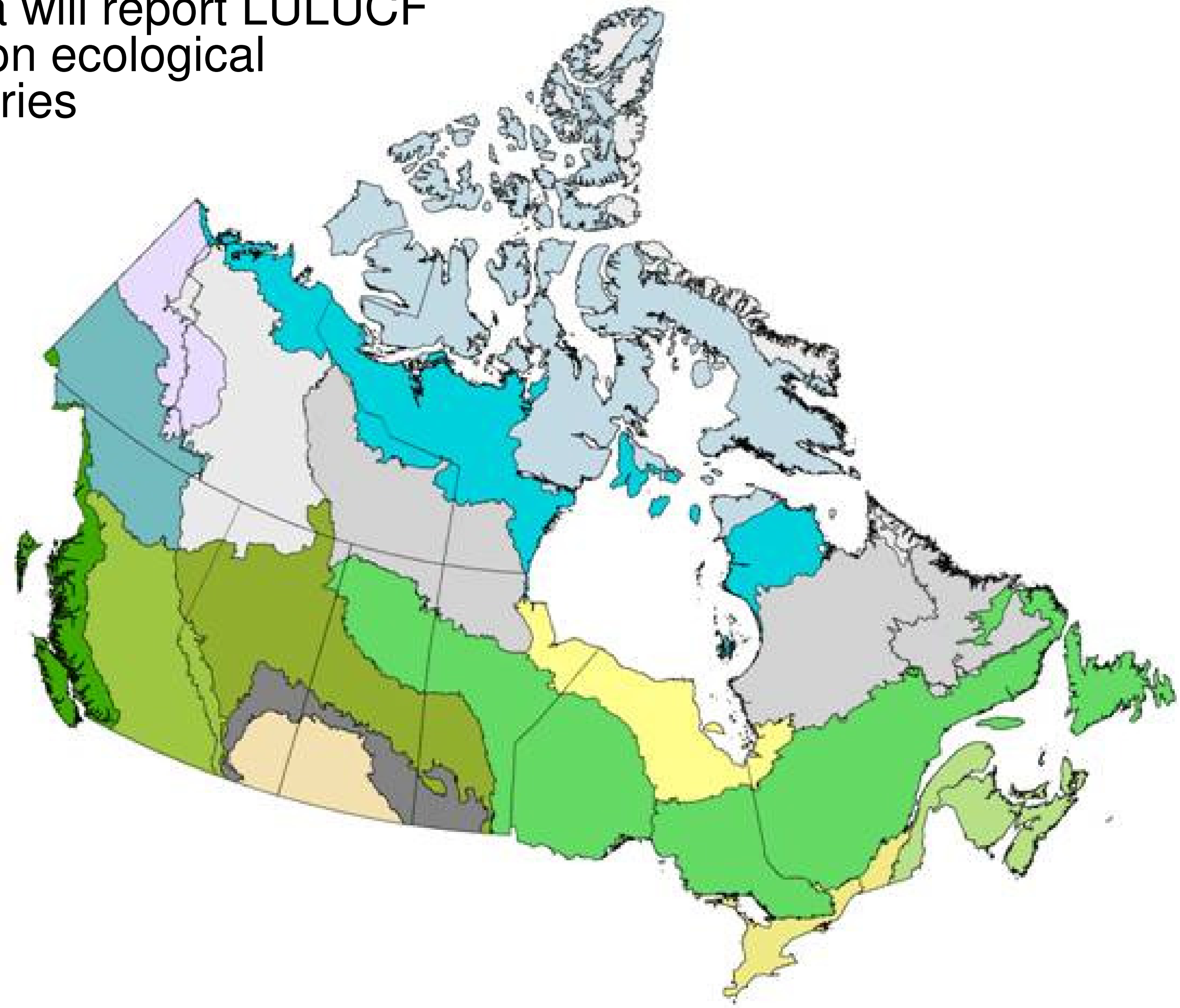

Soil Landscapes of Canada (SLC)
Polygon Land Database
Agricultural
Activity Databases
Nation
Province
Estimators for Deriving
GHG Emission/Removal Factors
Spatial Agricultural
Activity Database
Region or Reporting Unit
(Group of SLC Polygons)
Activities linked to GHG Factors
GHG Account
For SLC polygon

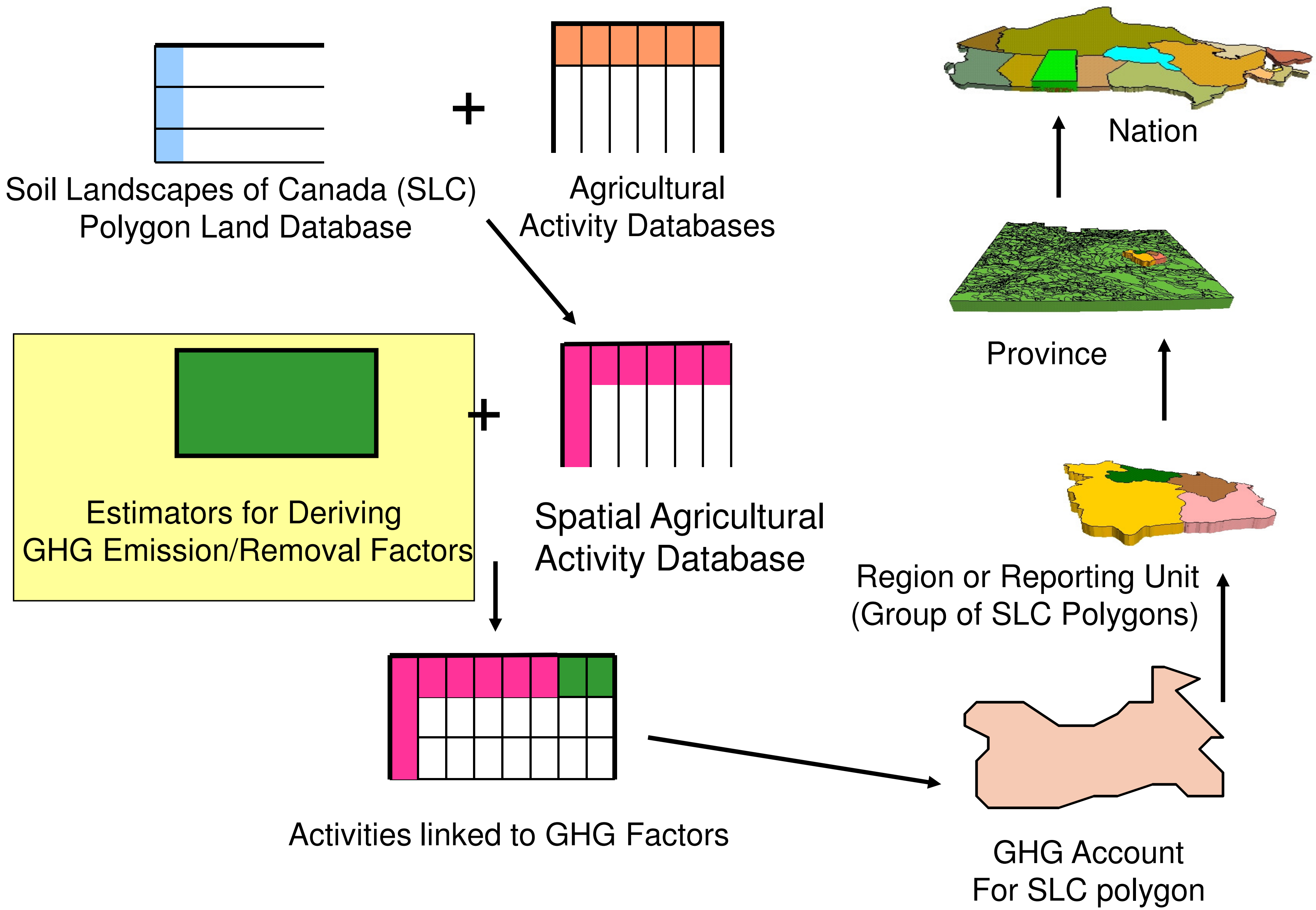
Ecostratification is a hierarchical national ecological framework



- Reporting Zone
  - Smallest area for which C change reported
- Calculation Unit
  - Soil component in SLC polygon

- Reporting Zones for which Canada will report LULUCF based on ecological boundaries

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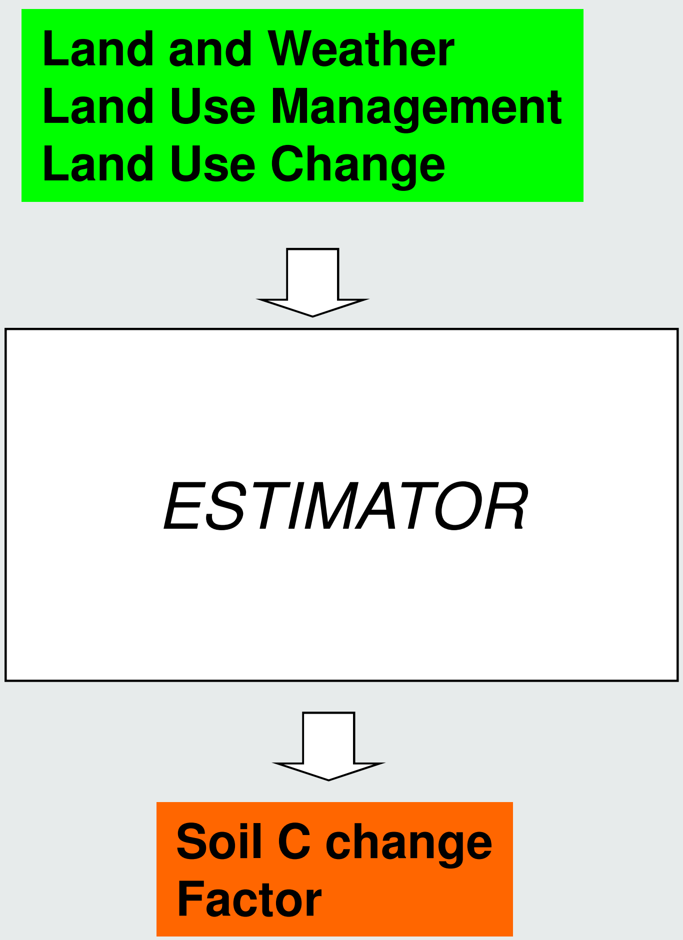
Estimators



- Estimator can be:
- Empirical relationship
  - Based on observed behaviour
  - Example: IPCC 1996 default methods
  - Canada-specific methods
- Mechanistic models
  - Example: CENTURY model of soil organic matter dynamics
  - Canada-specific application

Basic Equations for Factors

- $S_{y2} = S_{y1} + F_{y1\text{-}2} * A_{LUMC}$

- S_{y2} is carbon stock (Mg C) at year y2 from the land-use or management change (LUMC)
- S_{y1} is carbon stock at year y1 from the LUMC
- A_{LUMC} is the area of LUMC (ha) at y=0 (ha)
- $F_{y1\text{-}2}$ is the emission/removal factor for year y1 to y2 (Mg C/ha)

- $F_{y1\text{-}2}$ is the change in C between years y1 and y2 and is derived from the curve of change in C with time:

- $F_{y1\text{-}2} = [\Delta C_{LUMC}(y2) - \Delta C_{LUMC}(y1)]$

Net Area Change

- For land management changes known on net area basis, the area of net change may involve many gross area changes in land management
  - Example: 1500 ha decrease in intensive tillage (IT) and 1500 ha increase in no-till (NT) could be:
    - 1500 ha of IT going to NT
    - 2000 ha of NT going to IT and 3500 ha of IT going to NT
    - 1000 ha of Reduced Tillage (RT) going to NT + 500 ha of IT going to NT + 1000 ha of IT going to RT
    - 500 ha of RT going to NT + 500 ha of RT going to IT + 1000 ha of NT going to RT + 2000 ha of IT going to NT
    - *Ad infinitum*
- There are implied assumptions of linearity, reversibility, and additivity within LUMC known on net area changes

Assumptions for Net Area Basis

- Linearity
  - No interaction between factor and area of change
  - Total C change due to LUMC from A to B is

    $F_{A\text{->}B}$ x area involved
- Reversibility
  - Direction of LUMC does not affect magnitude of change

  $F_{A\text{->}B} = - F_{B\text{->}A}$

  Reversibility required assumption if to have no long-term large effect of LUMC that occurs but is soon reversed by opposing LUMC

Additivity

- Additivity:
  - Factor for LUMC from A to C , $F_{A\text{->}C}$ where A, B, and C are defined as mutually exclusive:

    $$F_{A\text{->}C} = F_{A\text{->}B} + F_{B\text{->}C}$$

    - Example: C change from change from intensive to reduced to no tillage assumed equal to change from intensive to no tillage
    - Correct in limit
  - Factor for LMCLUC from A to combination of C and D , $F_{A\text{->}CD}$ where C and D can exist together

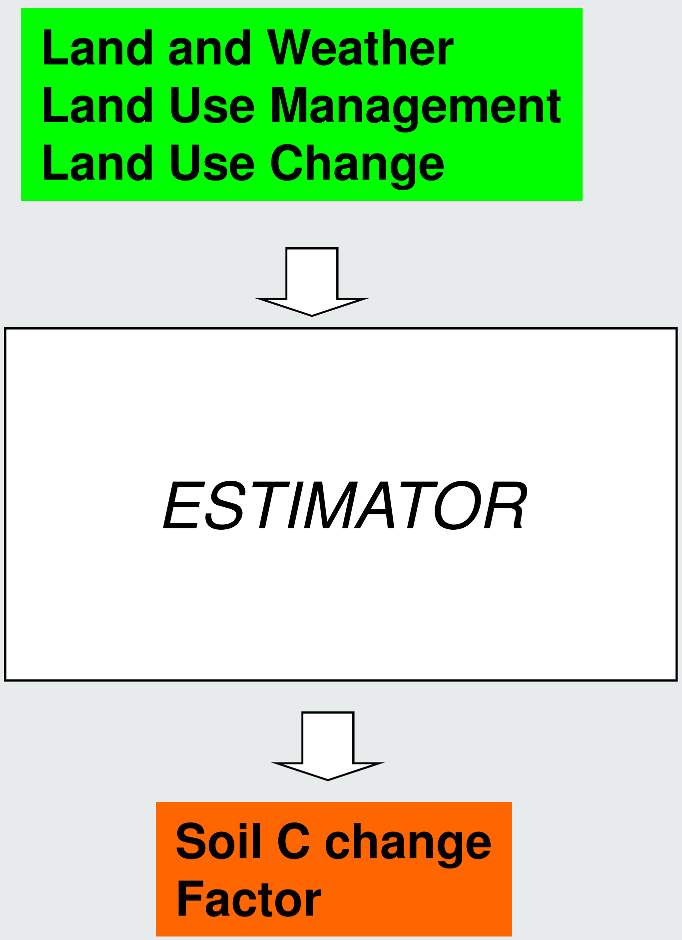
    $$F_{A\text{->}CD} = F_{A\text{->}C} + F_{A\text{->}D}$$

    - Example: C change from change from intensive tillage to no tillage on land also undergoing C stock change from recent change in summerfallow frequency

Activity on Gross Area Basis

- When know area of gross changes
  - Each area of gross change will have direction and vintage
  - (These are absolute requirements for LUC that is afforestation, reforestation, and deforestation)
- Assumption of factor reversibility or linearity not required

Estimators



- Estimator can be:
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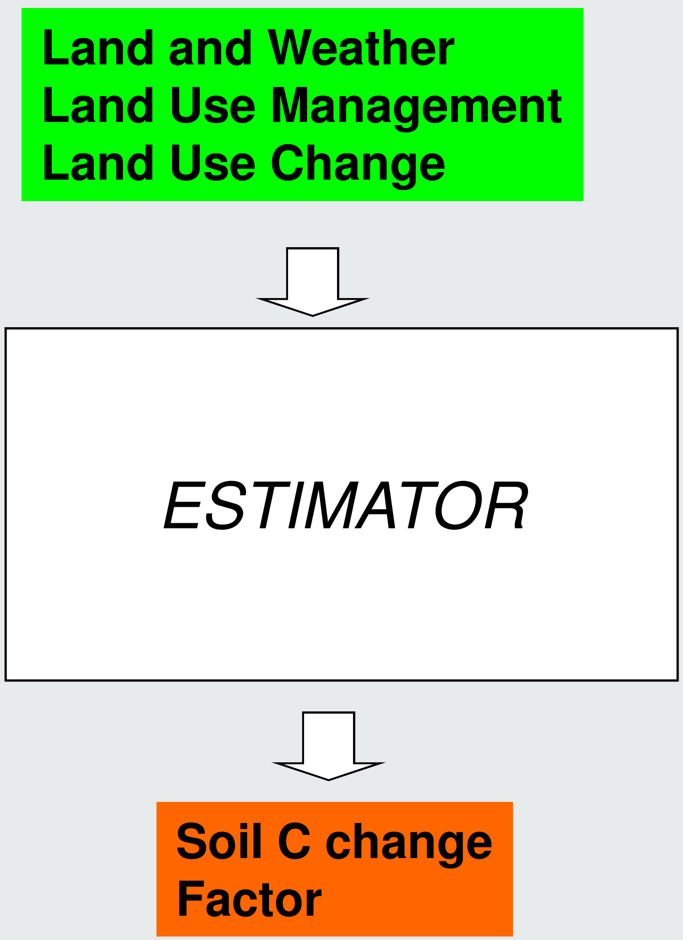
Factor Calculation

- Key assumption no C change with no LUMC
  - Inherent in IPCC Good Practice Guidance
  - Calculate factor as relative C change
- Factor is the C change with LUMC of interest less the C change without the LUMC
- More confidence in relative change than absolute change
  - Absolute change highly influenced by (generally uncertain) initial soil state

Estimators



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Empirical Determination

- ΔC_{LUMC} is estimated as the difference in C between two land use-management systems divided by the proportionate amount the LUMC between the two land use-management systems:
- $\Delta C_{LUMC}(y) = \Delta C / p_{LUMC}$
- where ΔC is the difference in C between land use-management systems and p_{LUMC} is the proportion of area of land use-management system that received the LUMC. This proportion can be derived as the proportion of the particular land use-management (LUM) in the base system less the amount of the LUM in the new system after LUMC. That is,
- $p_{LUMC} = p_{LUMbase} - p_{LUMnew}$

Empirical Factors

- Limited number of studies
  - Fallow reduction has best data
- Few measurements of C change over time
  - Difficult to determine duration of effect
  - Difficult to determine effect of time on factor
    - Usually assume linear rate of C change relative to no LUMC

Table 1. Example Empirical Data for Lethbridge Loam

Duration (yrs)	Treatment	SOC control (Mg ha^{-1})	Net C difference (Mg ha^{-1})
8	cont. w vs. f-w (all N fert)	27.7	4
8	f-w-w vs f-w (all N fert)	27.7	2
41	F-W-W vs. F-W (all no N fert)	29.3	0.8

Factor for fallow reduction

This factor would be the C change for each ha of reduced fallow. It can be calculated either from the continuous wheat (cont w) vs. fallow-wheat (fw) rotation or the fallow-wheat-wheat vs. fallow-wheat rotation.

i) from cont w vs. fw.

ΔC (8) = 4 Mg/ha

i.e. the change at year=8 is 4 Mg/ha

The LUMC is reducing fallow so the proportion the area which is fallow in the base system, $p_{LUMbase}$ is 0.5 while that after LUMC, p_{LUMnew}, is 0.

$p_{LUMC} = p_{LUMbase} – p_{LUMnew} = 0.5 – 0 = 0.5$

The C change due to the LUMC is:

$\Delta C_{LUMC}(8) = \Delta C / p_{LUMC} = 4/0.5 = 8$

Given the data limitations, we will assume linear factors.

The change occurred over 8 yr so the linear factor rate is:

Flin = 8/8 = 1 Mg C/ha/yr of fallow change

Other rotation comparisons within study

8-yr f-w-w vs. f-w: F_{lin} = 1.5 Mg C/ha/yr of fallow change

41-yr f-w-w vs. f-w: F_{lin} = 0.1 Mg C/ha/yr of fallow change

CENTURY based Factors

- Consistent approach possible
- Long history of use
- Open source code
- Gives time dependence and duration of effect

Steps for Century-based Factors

- Initialization of soil C state for subsequent Century runs
- Define base crop mix to be modeled
- Make LUMC of interest to the base crop mix
- Model C for 150 yr for the base crop mix (150 yr) and the crop mix with the LUMC
  - Use 1951-2000 weather repeated
- Calculate the difference in C with and without LUMC
- Derive Factor from that C difference

Century - Initialization

- SOC in SLC polygon soil layer database assumed to represent 1985 carbon level
- Started run in 1910 with 1.25 times the 1985 SOC
- Used generic early farming systems from Smith et al. (1997)* to 1980

*Smith, W.N., Rochette, P., Monreal, C., Desjardins, R.L., Pattey, E., and Jaques, A. 1997. The rate of carbon change in agricultural soils in Canada at the landscape level. Canadian Journal of Soil Science, 77: 219-229.

Base Crop Mix

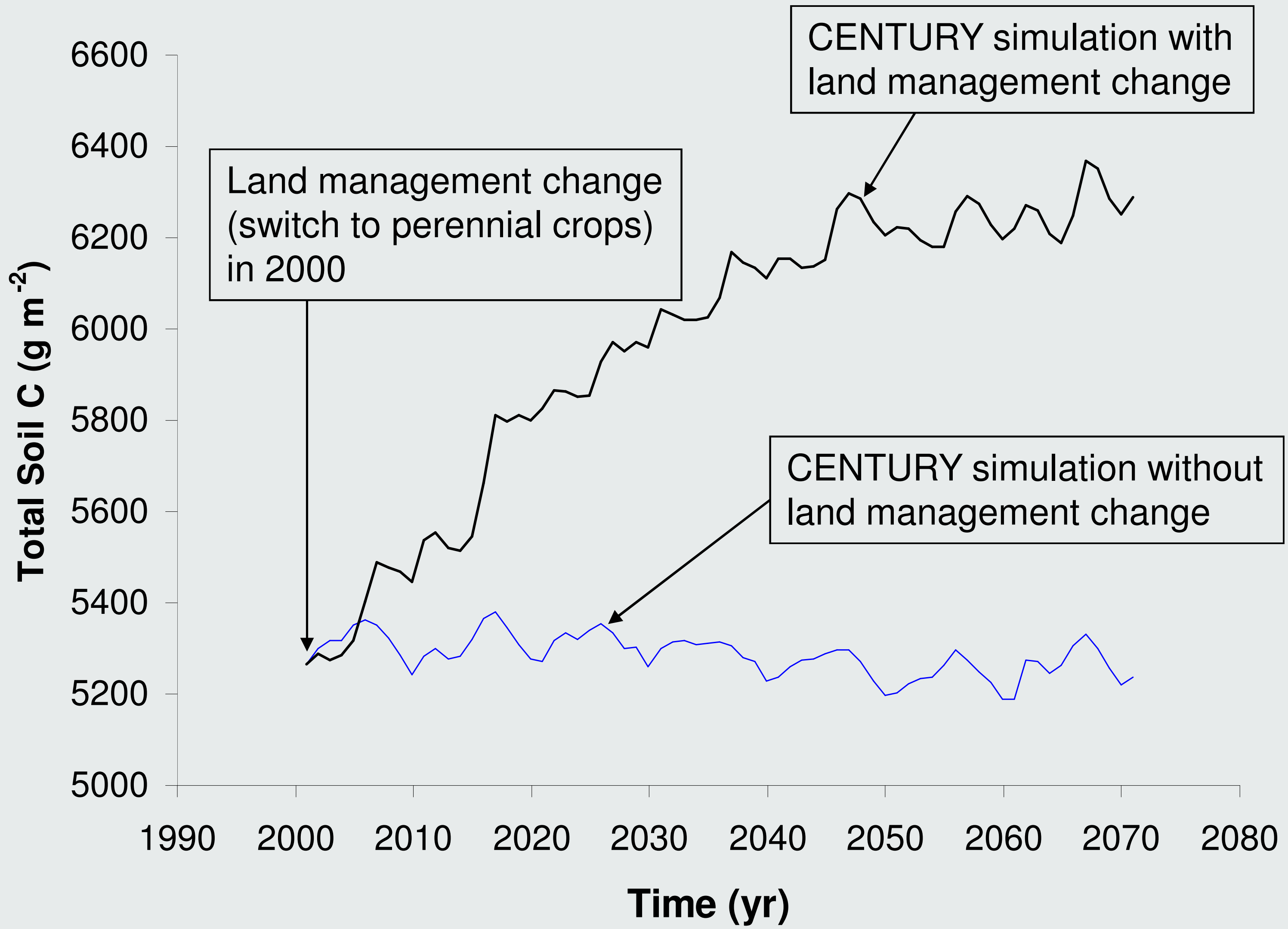
- Constructed base crop mix from 1991 Census data for each SLC polygon
- Include major crops with > 5% of area in SLC
  - All crops represented by generic field crops (wheat, canola, maize, soybean, potato, tame grass, or alfalfa)
  - Rule set for order of crops
- Tillage practices assigned to crops based on rule set
- Reproducible

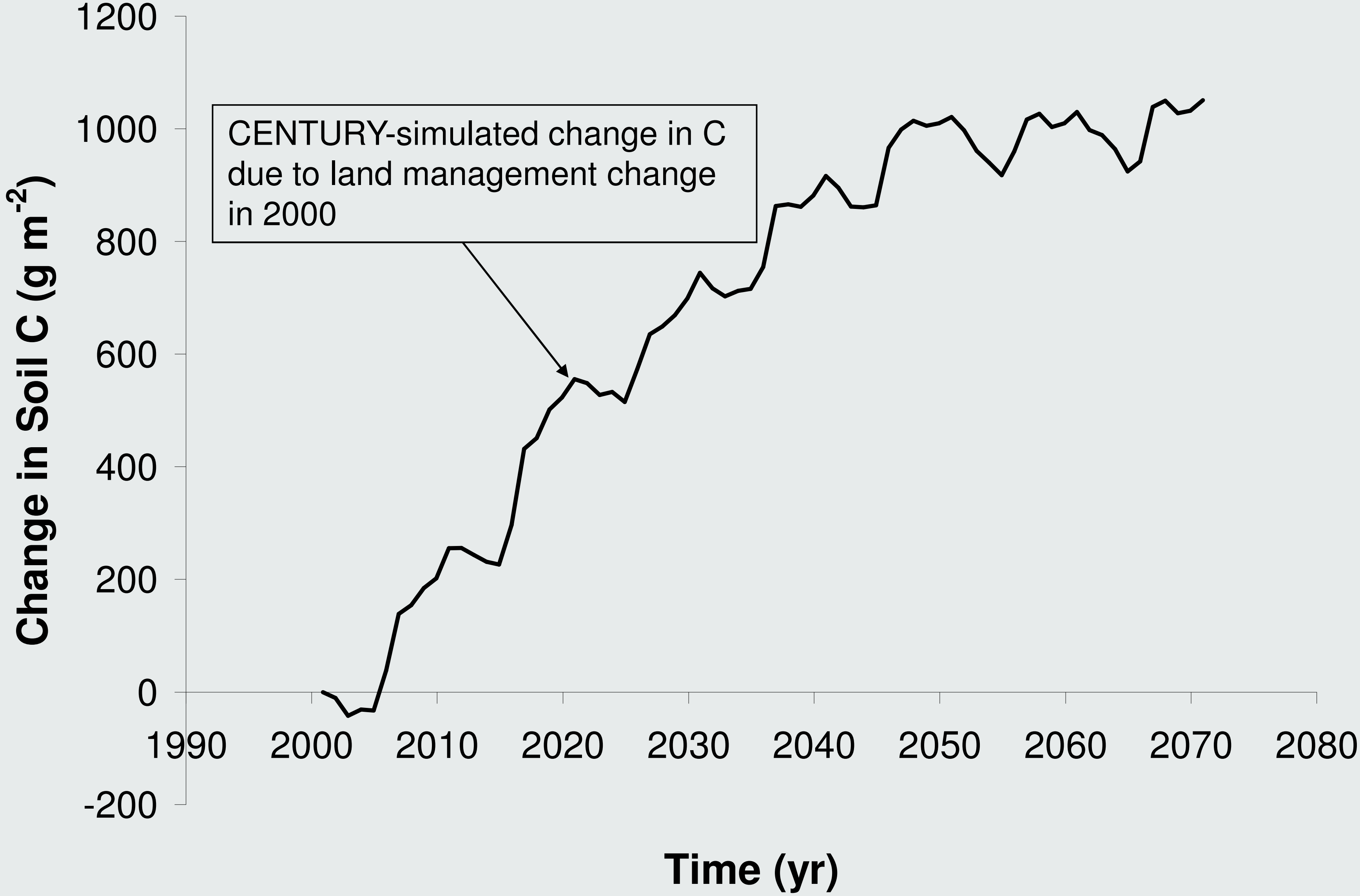
Base and Substituted Crop Mix

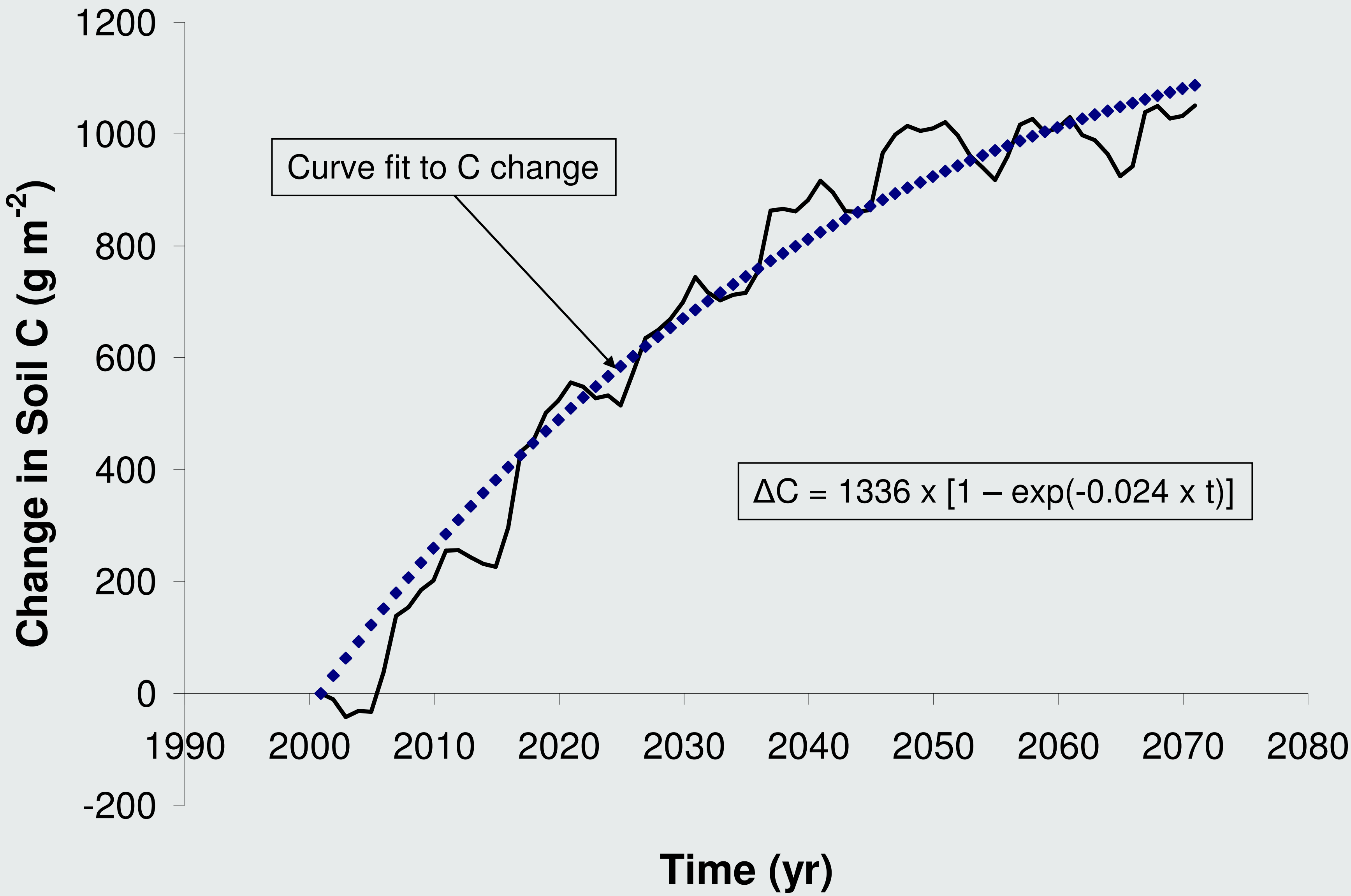
- Example 10-yr system:
  - Maize (intensive till)-soybean (no-till)-wheat (intensive till)-alfalfa-alfalfa-alfalfa(terminated with intensive till)-Maize (reduced till)-grass/alfalfa-grass/alfalfa (terminated with intensive till)-Maize (reduced till)
- To get intensive to no-till factor, substitute no-till for intensive till
  - Maize (no-till)-soybean (no-till)-wheat (no-till)-alfalfa-alfalfa-alfalfa (terminated with no-till)-Maize (reduced till)-grass/alfalfa-grass/alfalfa (terminated with no-till)-Maize (reduced till)

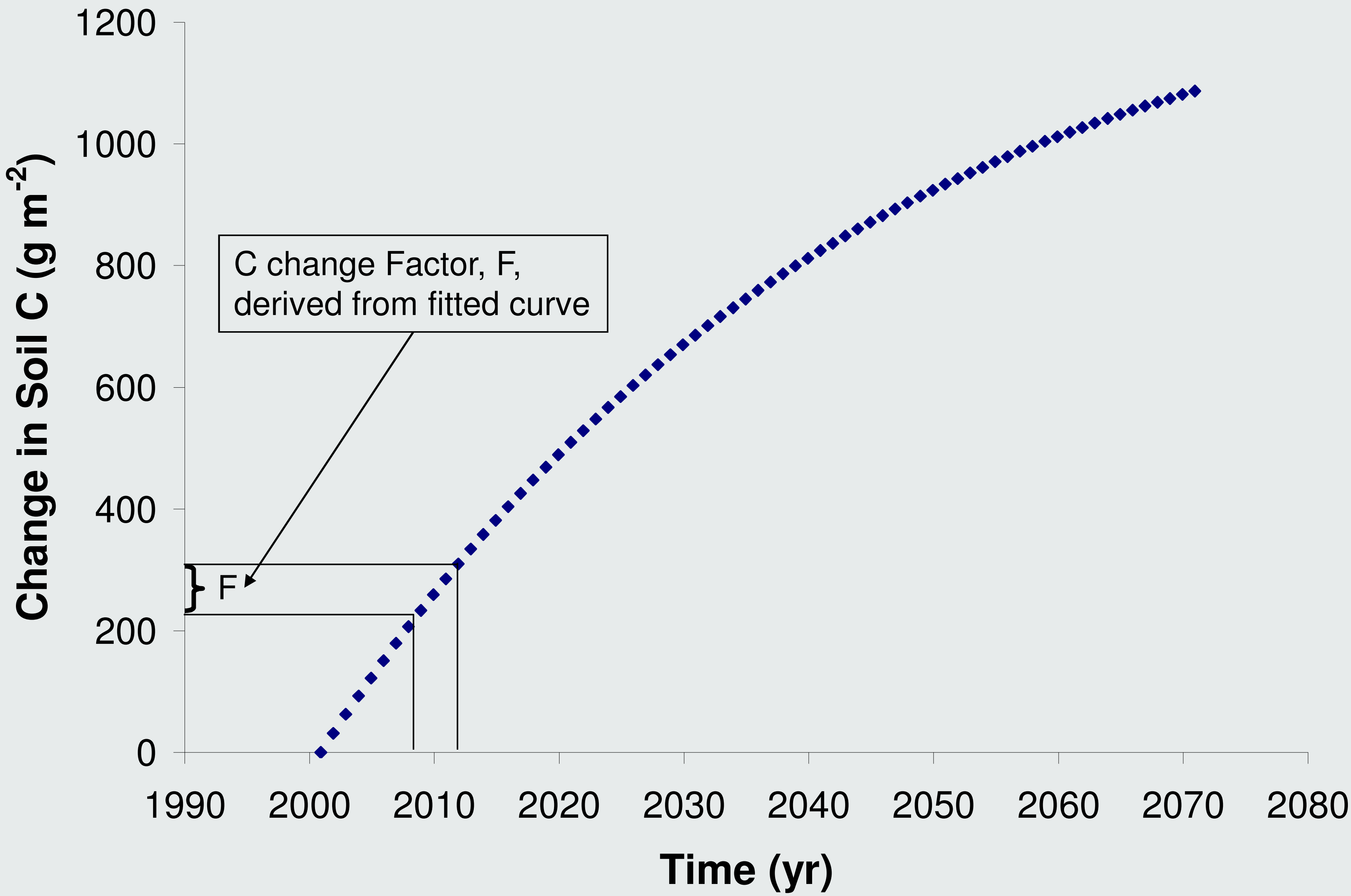
Factor Development

- Calculate ΔC_{LUMC} from difference between SOC for base mix and substituted mix
    - Base run simulates for base mix from 1980 to 2150
    - Substituted run, base mix from 1980 to 2000 and substituted mix from 2000 to 2150
- Fit exponential decay to the ΔC_{LUMC}
    - $\Delta C_{LUMC}(y) = \Delta C_{LUMCmax} * (1-\exp(-k*y))$
- Determine annual C change factor after adjusting for substitution proportion
    - $F_{y1\text{-}2} = [\Delta C\,(y2) - \Delta C\,(y1)]\ /pLUMC$
- When $F_{y1\text{-}2}$ drops below 25 kg C ha^{-1} then neglect all subsequent ΔC_{LUMC}


CENTURY simulation with
land management change
Land management change
(switch to perennial crops)
in 2000
CENTURY simulation without
land management change
Total Soil C (g m-2)
6600
6400
6200
6000
5800
5600
5400
5200
5000
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
Time (yr)

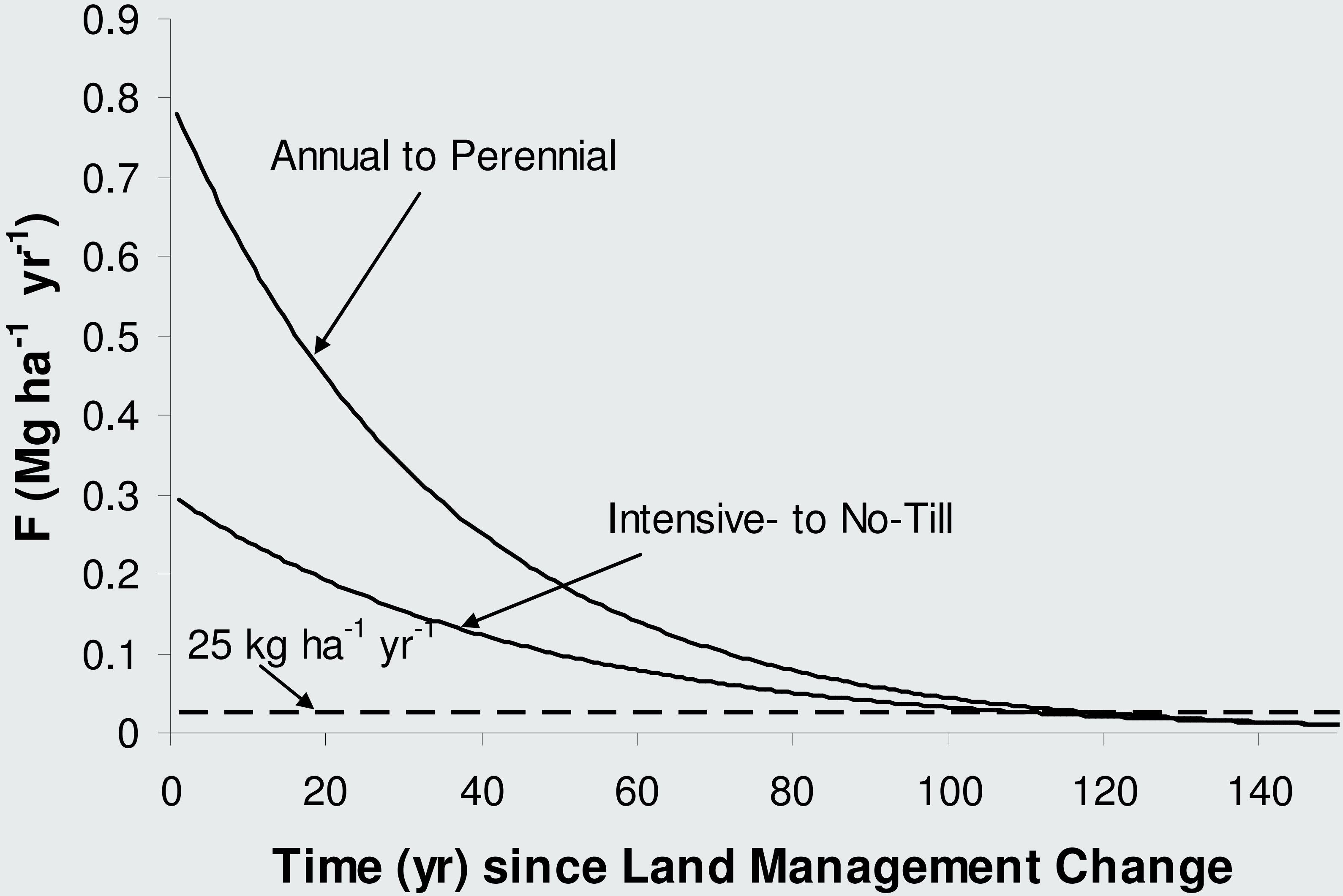

CENTURY-simulated change in C due to land management change in 2000
Change in Soil C (g m-2)
1200
1000
800
600
400
200
0
-200
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
Time (yr)


Change in Soil C (g m-2)
1200
1000
800
600
400
200
0
-200
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
Time (yr)
Curve fit to C change
ΔC = 1336 x [1 – exp(-0.024 x t)]



C change Factor, F,
derived from fitted curve
F
Change in Soil C (g m-2)
Time (yr)
0
200
400
600
800
1000
1200
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080

Factor change with time

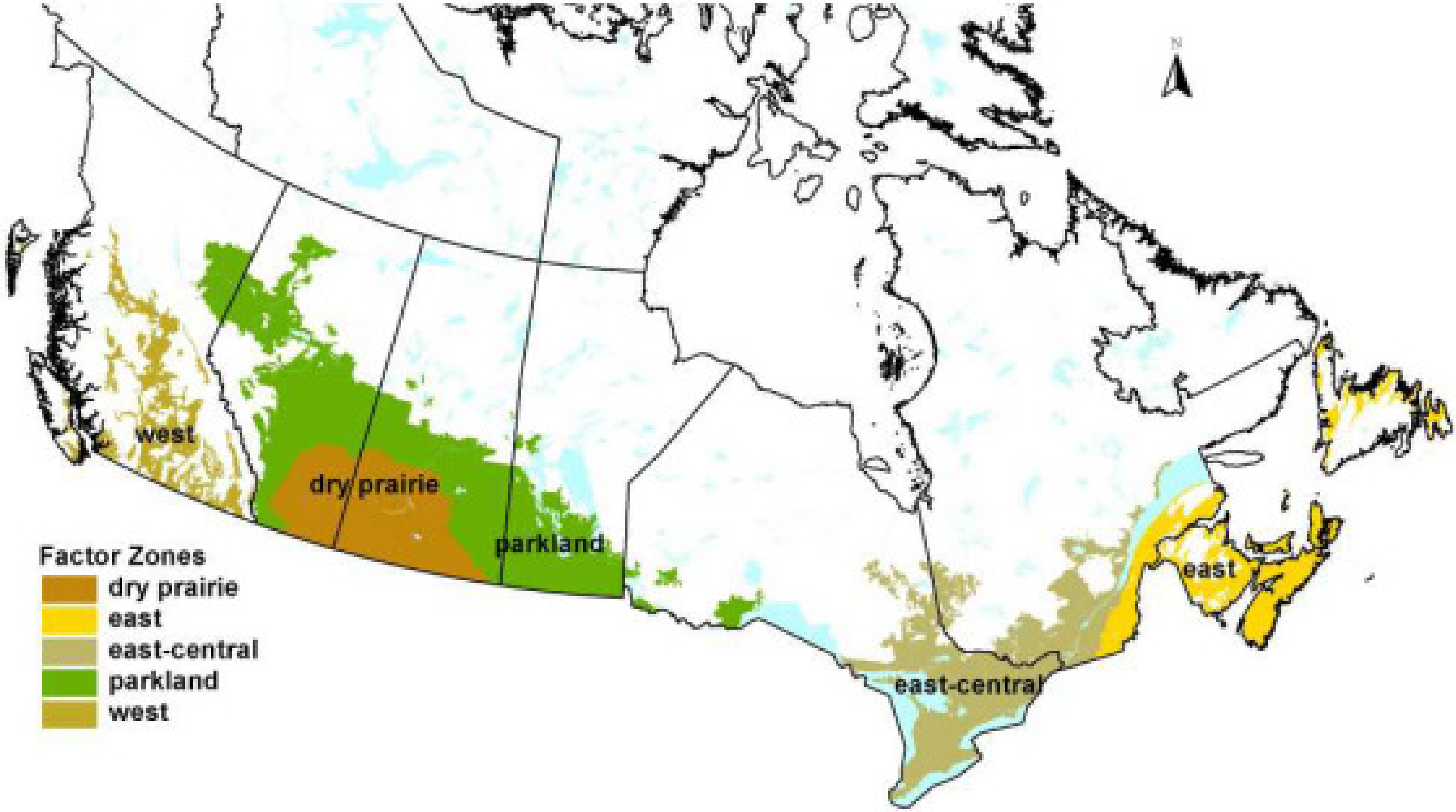


Results

- Exponential equation fit well generally
- Wide variation in simulated change among soil components and SLC polygons
  - Information used to assess uncertainty at reporting zone scale
- Decided to derive average factor values for general textural class (coarse-, medium-, fine-textured) at reporting zone scale
  - Difficult to know if any within reporting zone differences were real
  - Able to validate at reporting zone scale, less confidence at finer resolution
- Paper on validation of reporting-zone factors is in press (CJSS)

Validation (IT to NT)

Region	Average C factors			
	Long-term Experiments[z]			Predicted
	n	C change factor ($Mg\ ha^{-1}yr^{-1}$)	Standard Deviation	C change factor ($Mg\ ha^{-1}yr^{-1}$)
Semiarid Prairie	8	0.05	0.15	0.11
Subhumid Prairie	9	0.22	0.25	0.16
East Central	3	0.06	0.14	0.10
East Atlantic	1	-0.26	n/a	0.06


N
west
dry prairie
parkland
east-central
east
Factor Zones
dry prairie
east
east-central
parkland
west

zones of Canada

Zone[y]	LMC	Canadian Inventory: k (year^{-1})	Canadian Inventory: ΔSOC_{max} (Mg ha^{-1})	Canadian Inventory: 20-year average factor (Mg ha^{-1} yr^{-1})	IPCC Tier 1: ΔSOC (Mg ha^{-1})	IPCC Tier 1: 20-year annual factor (Mg ha^{-1} yr^{-1})
East Atlantic	CT to NT	0.022	3.5	0.06	9.9±12.4[z]	0.49±0.62
	Decrease Fallow	0.031	13.1	0.30	10.5±13.6	0.52±0.68
	Increase perennials	0.022	43.4	0.77	42.8±7.8	2.14±0.39
East Central	CT to NT	0.025	5.0	0.10	9.9±12.4	0.49±0.62
	Decrease Fallow	0.031	13.1	0.30	10.5±13.6	0.52±0.68
	Increase perennials	0.025	38.2	0.74	42.8±7.8	2.14±0.39
Subhumid Prairies	CT to NT	0.029	6.5	0.14	4.6±13.2	0.23±0.66
	Decrease Fallow	0.031	13.1	0.30	21.1±14.3	1.05±0.72
	Increase perennials	0.023	29.4	0.55	37.5±9.2	1.87±0.46
Semiarid Prairies	CT to NT	0.026	4.9	0.10	3.2±6.3	0.16±0.31
	Decrease Fallow	0.031	13.1	0.30	5.6±7.4	0.28±0.37
	Increase perennials	0.028	26.1	0.56	12.0±6.0	0.60±0.30
West Pacific	CT to NT	0.012	4.8	0.05	9.9±12.4	0.49±0.62
	Decrease Fallow	0.031	13.1	0.30	10.5±13.6	0.52±0.68
	Increase perennials	0.016	34.4	0.46	42.8±7.8	2.14±0.39

Carbon Storage in Soils of the North American Great Plains: Effect of Cropping Frequency

C. A. Campbell,* H. H. Janzen, K. Paustian, E. G. Gregorich, L. Sherrod, B. C. Liang, and R. P. Zentner

Agron. J. 97:349–363 (2005)

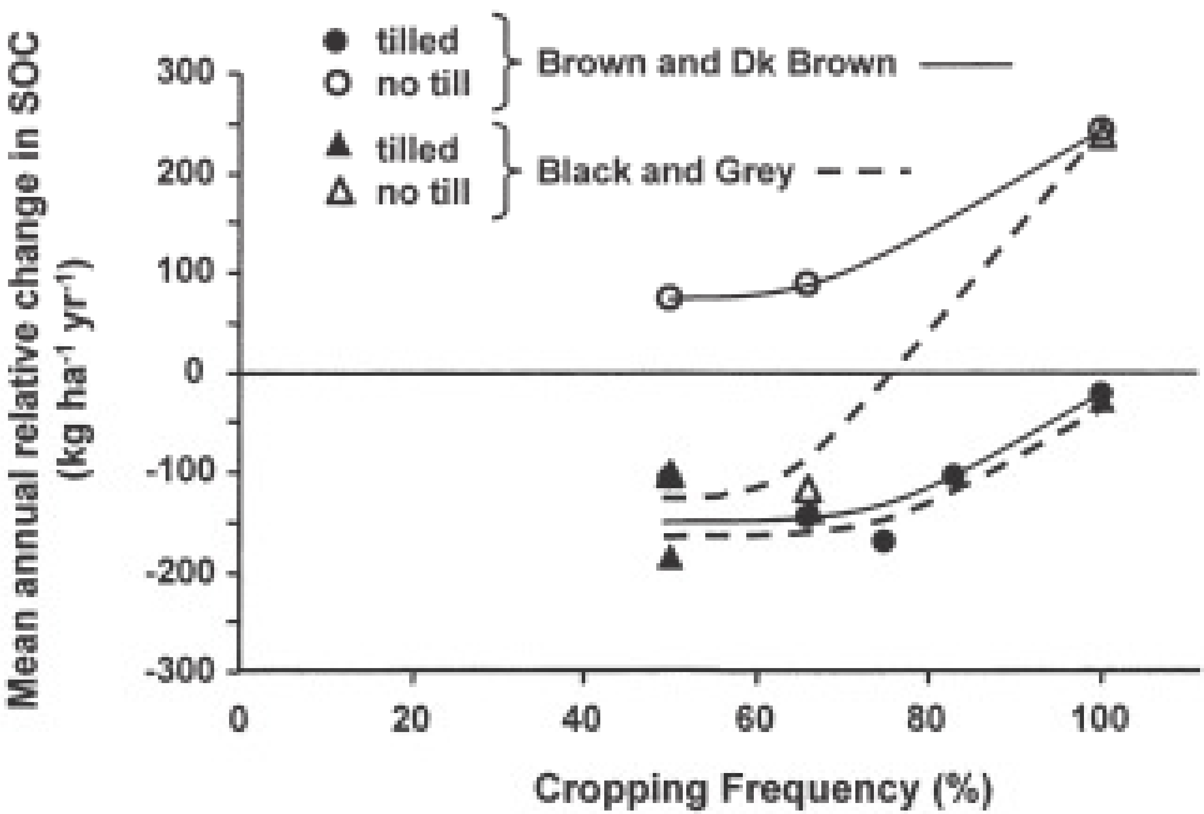
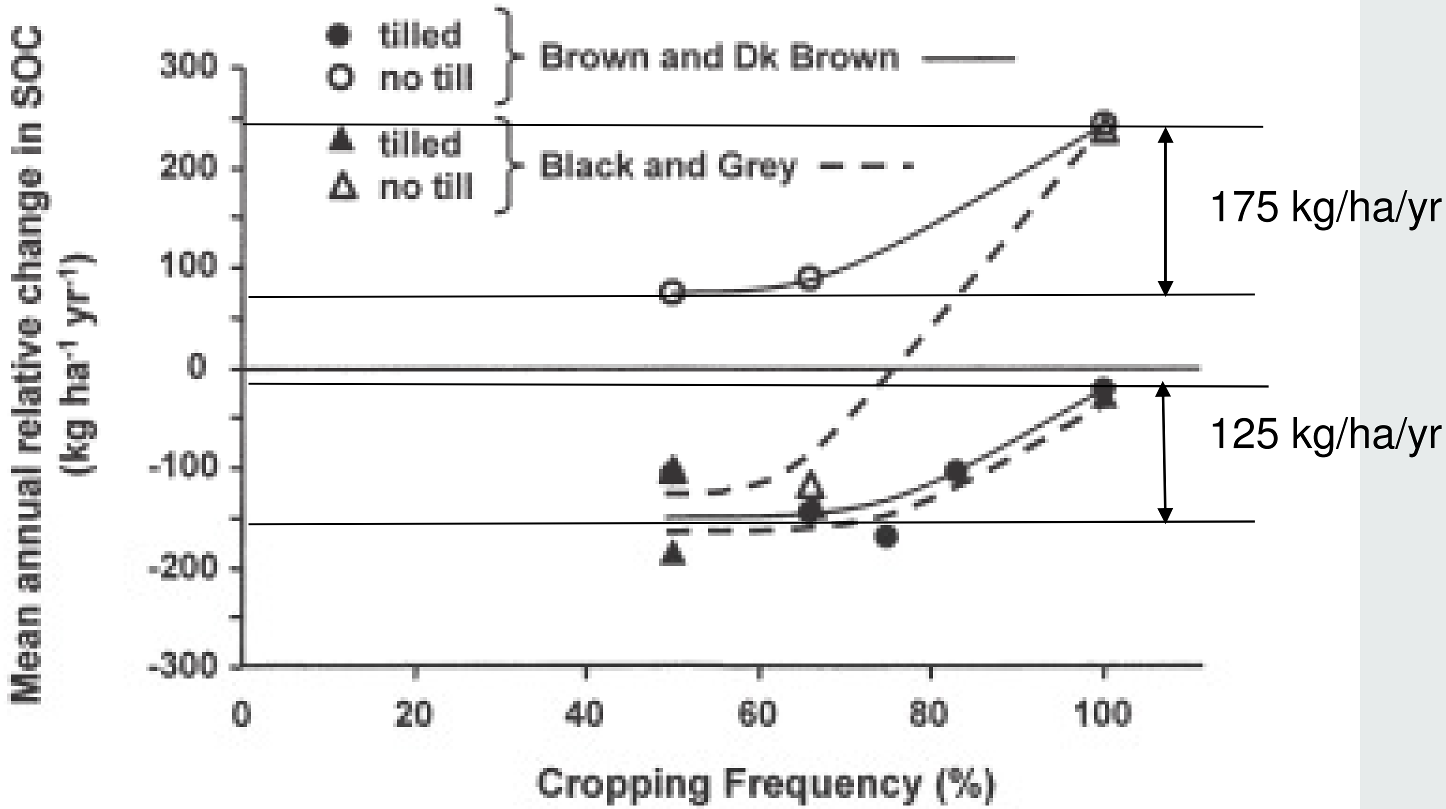


Fig. 8. Effect of cropping frequency on mean annual rate of change in soil organic C (SOC) relative to well-fertilized continuous cropping, tilled treatments (control) in Canadian Prairie studies (developed from data in Table 5).



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Summerfallow

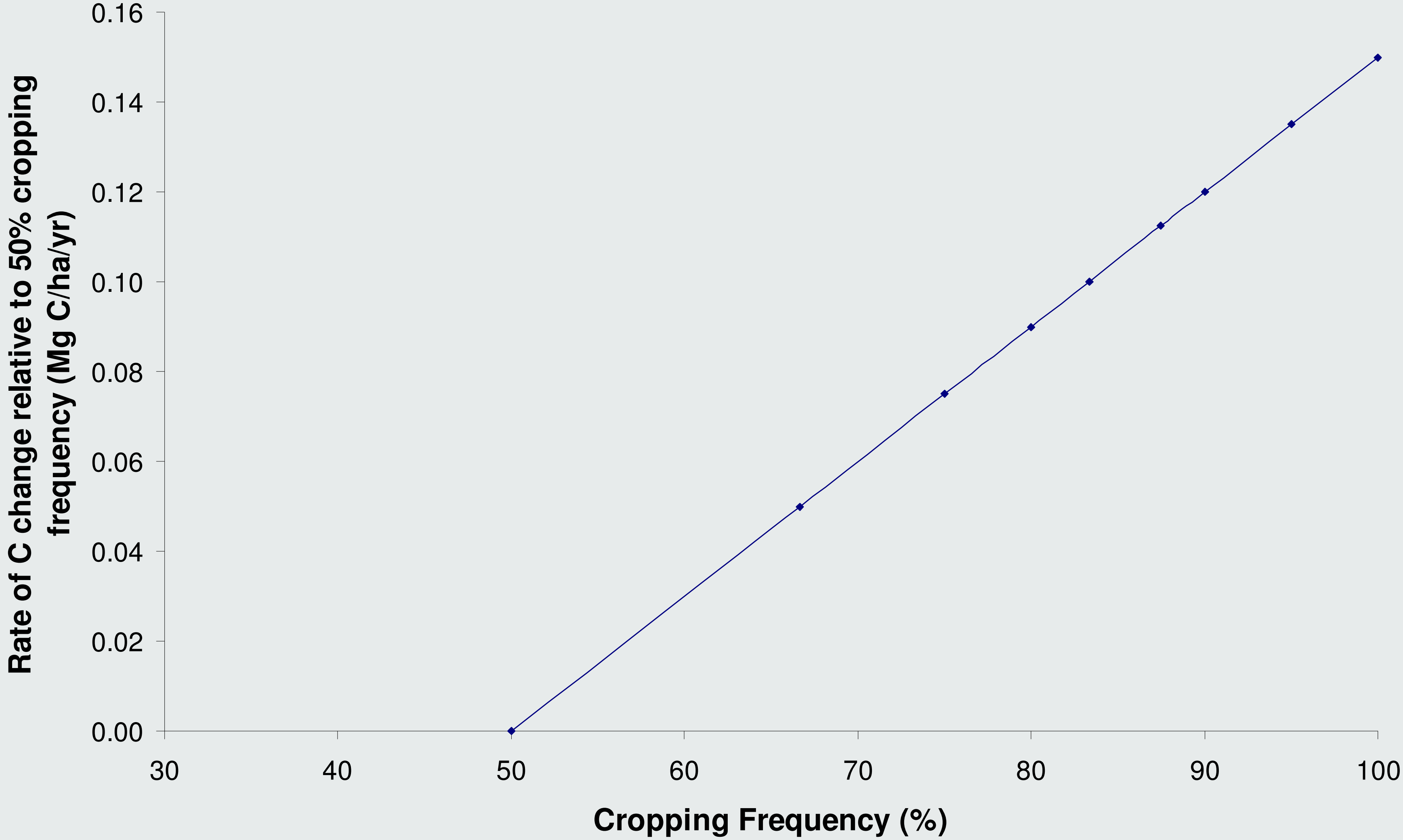
- Century predicted $\Delta C_{LUMCmax}$ for fallow about 26 Mg/ha for Brown/Dark Brown and 35 Mg/ha for Black/Gray soil zone
  - Century may be overestimating effect because of perennial crops in base and substituted mixes
- IPCC recommends $\Delta C_{LUMCmax}$ for fallow increase/decrease of 21.1±14.3 Mg/ha for Black/Gray soil zone and 5.6±14.3 Mg/ha for Brown/Dark Brown soil zone
- Scaled $\Delta C_{LUMCmax}$ for fallow to Campbell et al. (2005) as “expert” opinion of summerfallow effect but still using Century for dynamics (i.e. the “k”)
  - $\Delta C_{LUMCmax}$ = 13.1 Mg/ha
  - Change similar to average of IPCC values for prairies
  - “conservative” value (?)

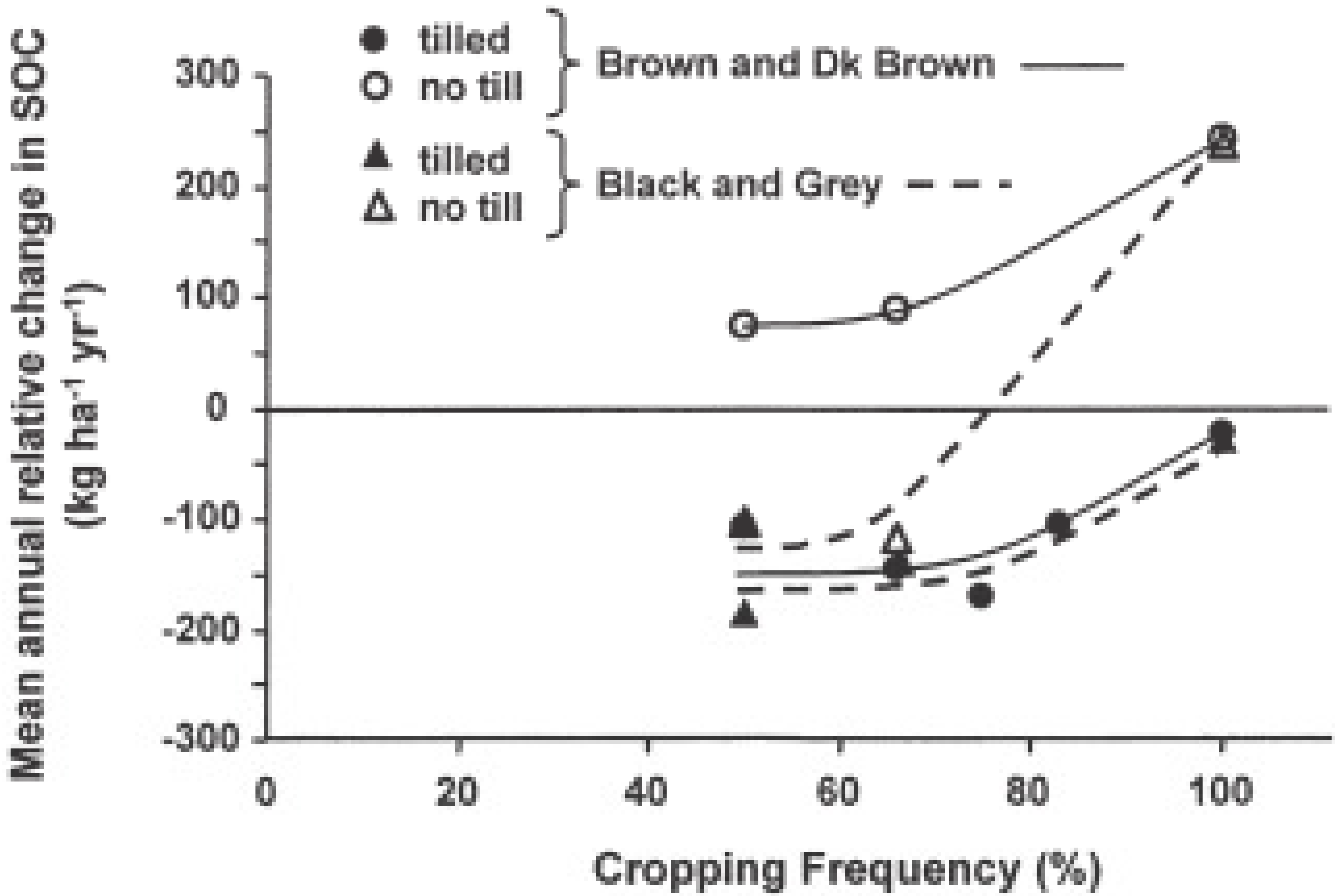
Re-analysis of Canadian empirical values

- Brown/Dark Brown soil zone
  - $\Delta C_{LUMCmax}$ = 23.3 Mg/ha (n=51 rotation comparisons)
- Black/Gray soil zone
  - $\Delta C_{LUMCmax}$ = 7.7 Mg/ha (n=7)
- (Average prairie $\Delta C_{LUMCmax}$ = 15.5 Mg/ha)

- Linearity assumption needed to deal with net area changes requires that effect of frequency of summerfallow change be linear function of proportional change in fallow frequency
- Therefore, easiest to express change in terms of unit area of fallow rather than any assumed rotation
  - E.g. if 1347 hectares less fallow in 5922 ha of cropland, then
  - C change is 1347 * F regardless of
  - (without more knowledge, infinite number of feasible combinations of actual rotation changes involving fallow change could be underneath this change)

Linearity assumption of effect of fallow frequency





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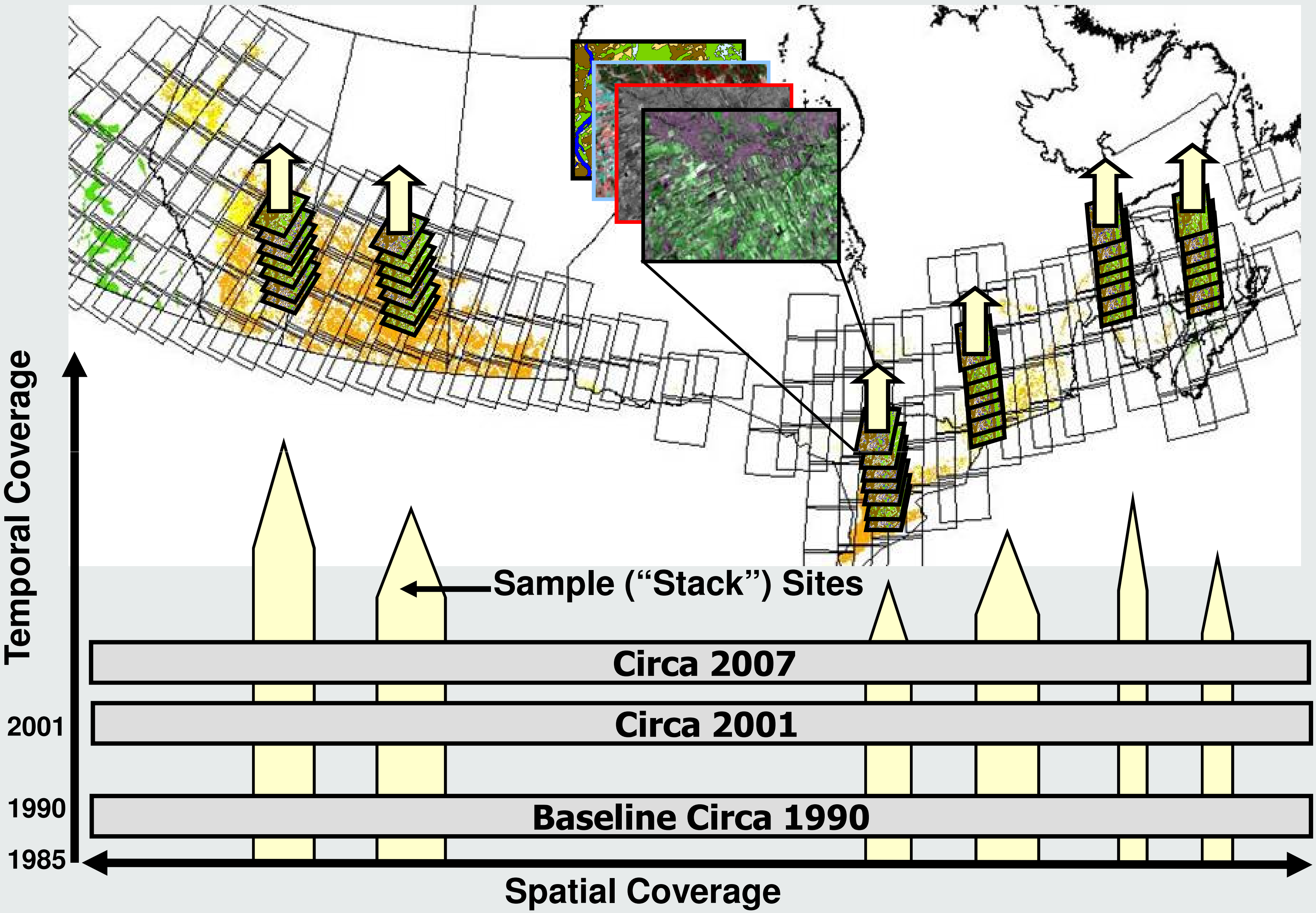
Thoughts on Quantification for Offset System

- Inventory factors useful for default protocols
  - Have effective baseline of no LUMC
  - Ensure project emission reductions represent what counted in national inventory
- Project-specific factors
  - If verified data could be specific to project
  - Summerfallow can be reliably detected with thematic (NIR, R, G) images from July

Land Use from Earth Observation



Additivity

- Additivity means no interaction between C change due to summerfallow change and tillage
- McConkey et al. (2003) report on four experiments in Western Canada and found no interaction between tillage and rotation. Peterson et al. (1998) summarized results from many experiments in the Great Plains of the United States and concluded that reducing tillage increased soil C across rotations and reducing fallow increased soil C across tillage treatments without clear interactions. West and Post (2002) did an analysis of world-wide literature and did not find an interaction between rotation and tillage excepting that reduction in tillage in wheat-fallow systems had less impact on soil C than in other rotations. The results from single experiments are inconclusive as some have showed interactions between tillage and rotation (Halvorson et al., 2002a; Huggins et al., 2007) whereas other studies have not shown significant interactions (Halvorson et al., 2002b; Yang and Kay, 2001).

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Questions?

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