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C-14 Background, Pathway, and Dose Calculation Analysis

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2013 RETS/REMP & GROUNDWATER PROTECTION WORKSHOPS

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Background

Objective: Develop technical bases and guidance for enhanced accuracy and precision of carbon-14 dose estimates.

- Continuation of "C-14 Dose Calculation Methods at Nuclear Power Plants" EPRI Report 1024827
- Regulatory Guide 1.109 Revision 1 Issued 1977 Based on ICRP 2
  - Encompasses Many of the Limitations of the Time
  - Recommendations of the ICRP Have Changed substantially
  - Several Parameters in the Calculation of C-14 Dose Changed Since 1977
- The Understanding of C-14 in the Environment has Evolved Significantly in Recent Years

Approach

- Extensive Literature Search Conducted
  - C-14 Behavior in the Environment
- Assessment of Radiocarbon Dating Industry for Detection of C-14
  - Accelerator Mass Spectrometry (AMS)
- Case Studies at Nuclear Power Plants Using AMS
  - Two Sites
- Comparisons to Regulatory Guide 1.109
  - Several Improvement Opportunities and Updates

Radiocarbon Laboratories & Analysis

- Units & Terms Used by Radiocarbon Laboratories
  - Radiocarbon Age
  - Fraction or % Modern Carbon (pMC)
  - Δ14C
  - Specific Activity (Bq/kg C or pCi/kg C)
  - Reference Standards
- Conversion of % Modern Carbon to Concentration C-14 (pCi/kg Fresh Weight of Sample)
- Accuracy and Precision for AMS

Percent Modern Carbon in the Troposphere during and Following Weapons Testing

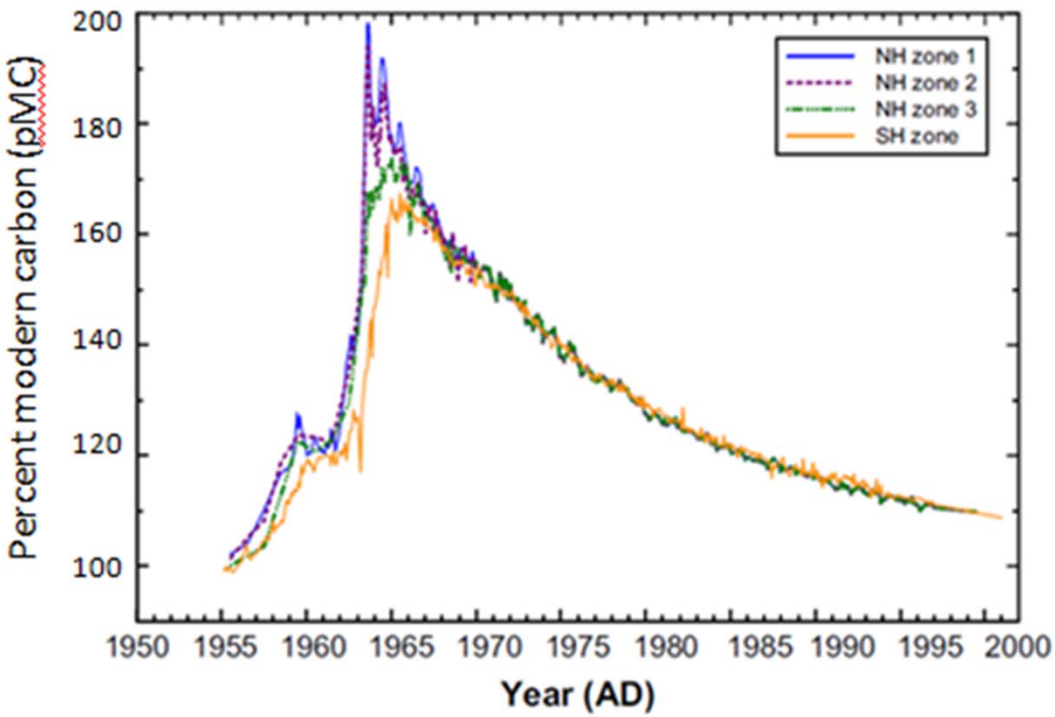

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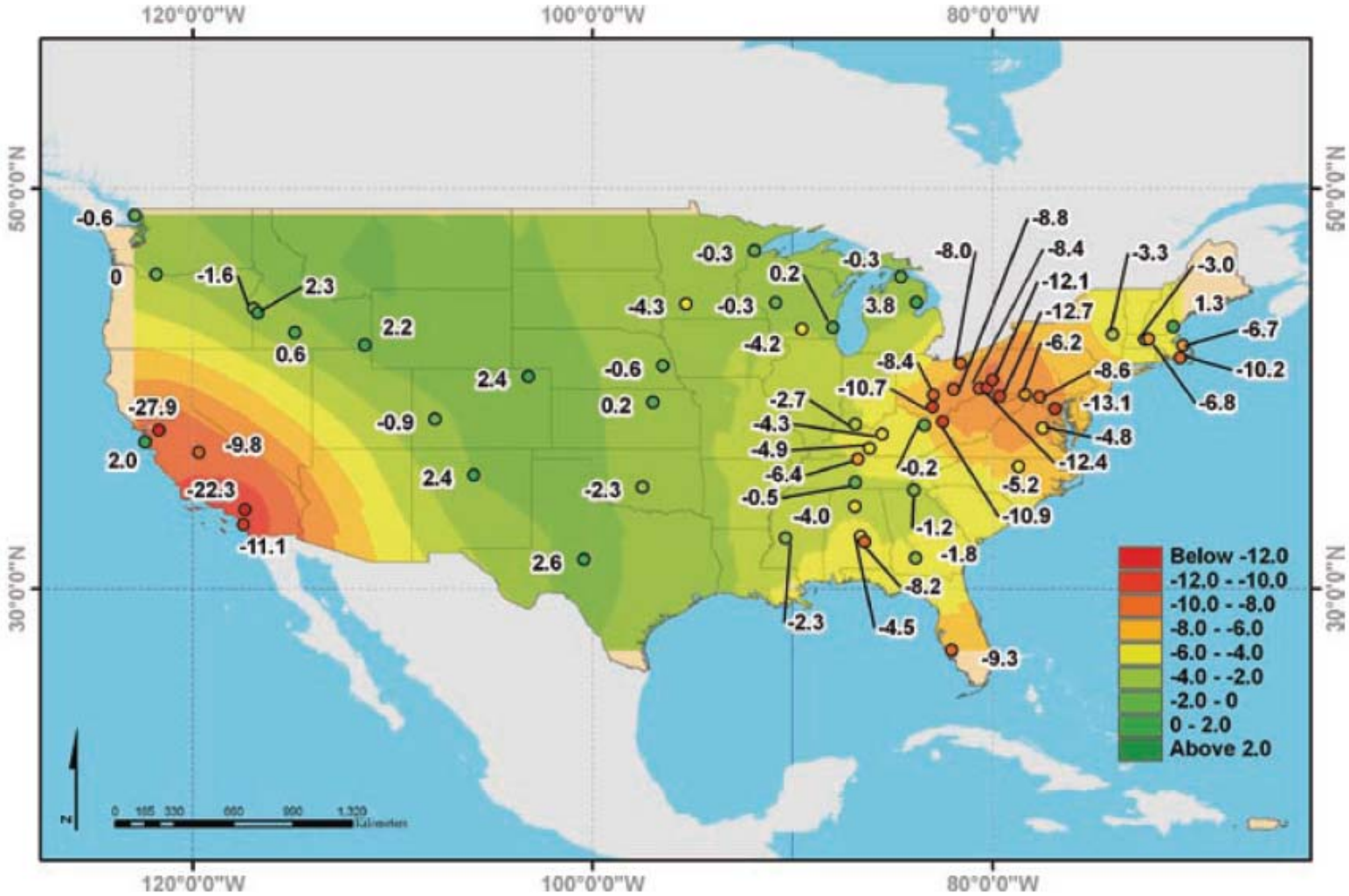
Illustration of Localized $^{14}CO_2$ Signatures (Δ14C)



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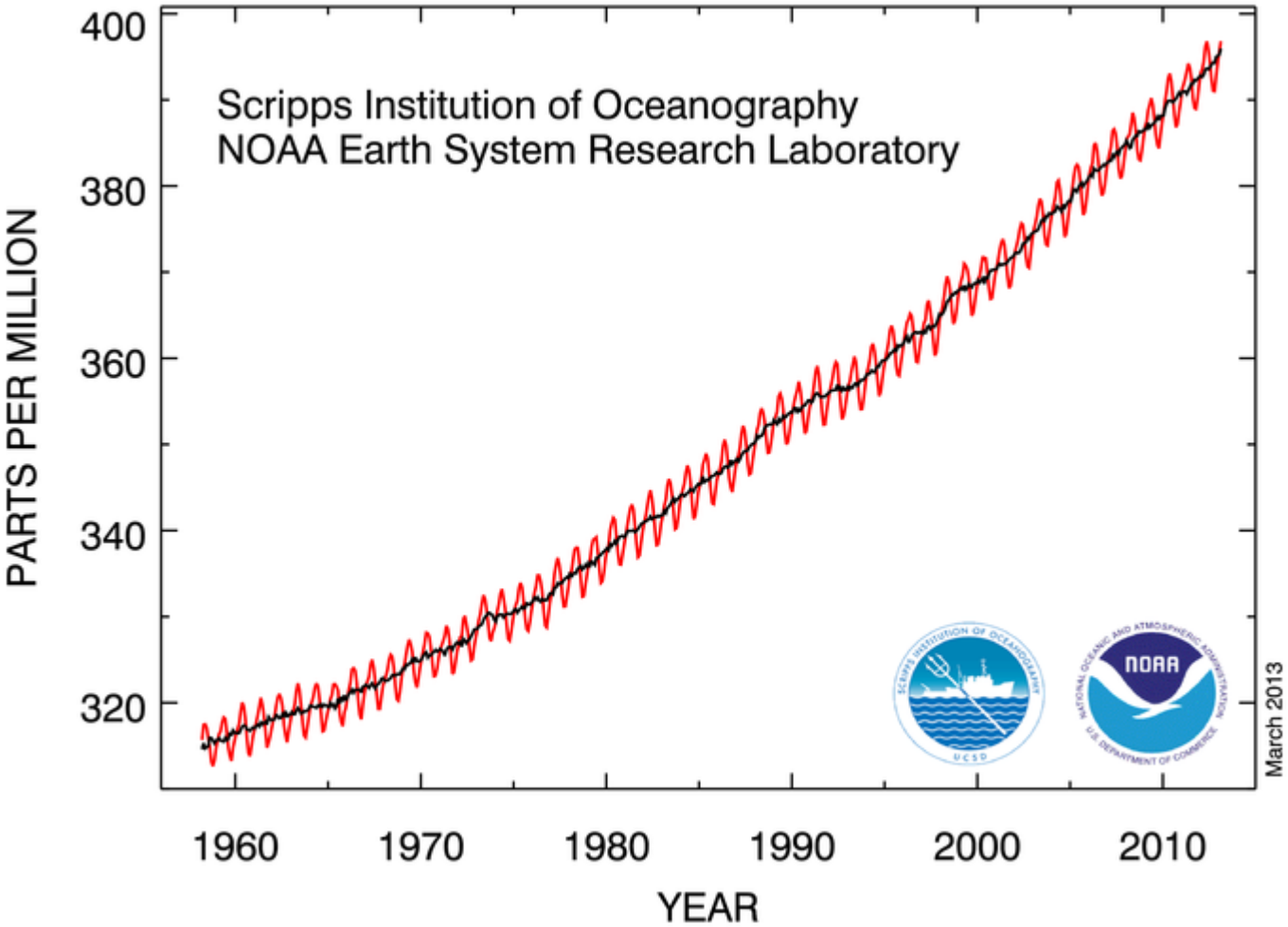
Suess Effect, Trends in CO_2 Releases



Atmospheric CO_2 Recorded at Mauna Loa Observatory (Tans & R. Keeling 2013)

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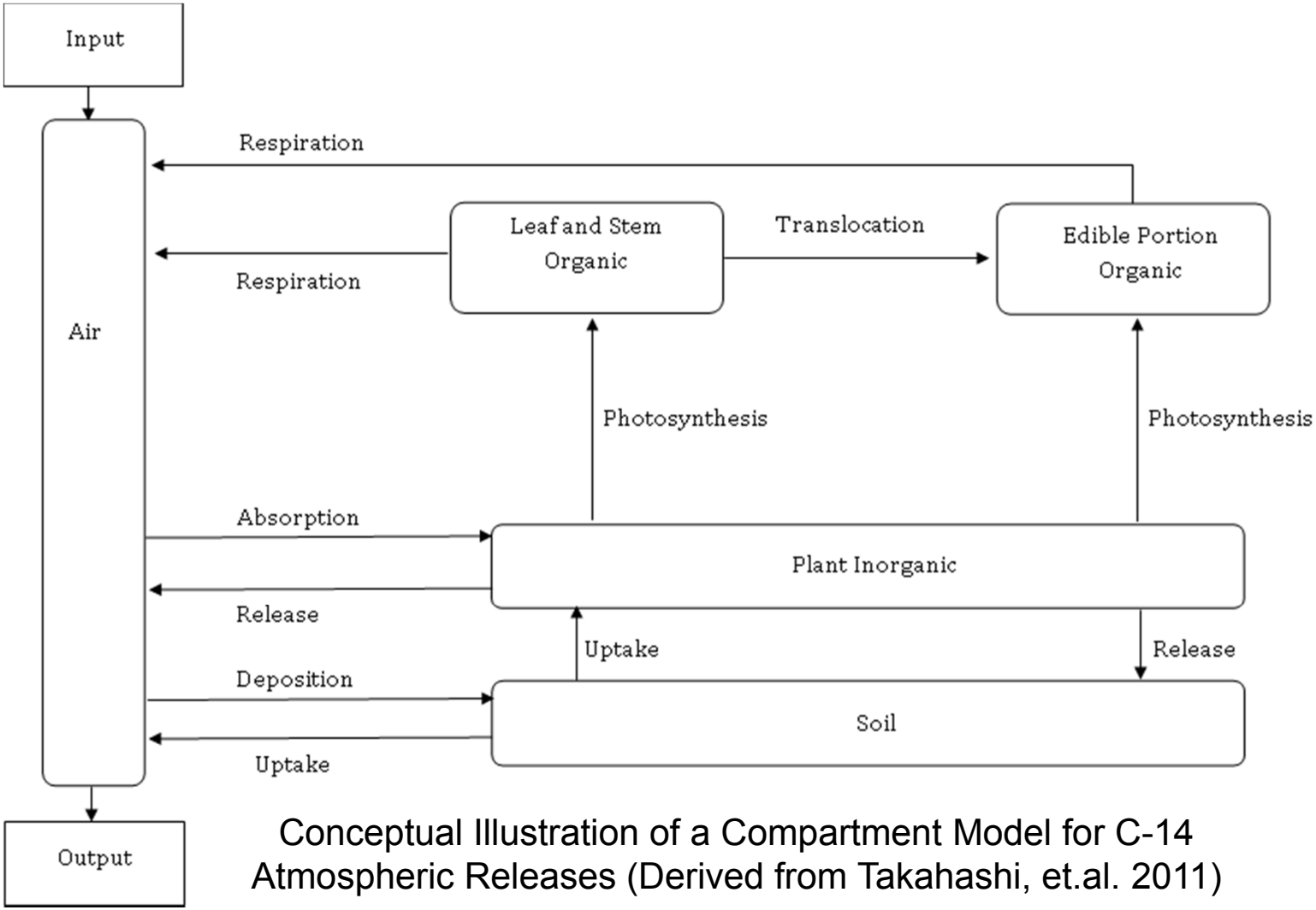
C-14 in the Environment

- Models of Carbon Distribution in the Environment
  - Specific Activity Models (Everything is in Equilibrium)
  - Compartment Models
- Transfer Mechanisms for Carbon in Plants
  - Less Than 2% of the Total Carbon in Plants is Provided through the Roots
  - More than 98% if the Total Carbon in Plants is Provided by Photosynthesis Fixing Carbon from the Air
- Photorespiration
  - High Temperature and Low Moisture

Example Compartment Model for Carbon in Plants



Conceptual Illustration of a Compartment Model for C-14 Atmospheric Releases (Derived from Takahashi, et.al. 2011)

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Carbon Inventories

- Inventories*
  - Ocean Inventory 38,000 Pg C
    (P is 10^{15})
  - Atmospheric Inventory 730 Pg C
  - Terrestrial Inventory 2,200 Pg C
- Most Carbon Eventually Resides in the Oceans

*Matsumoto & R. M. Key 2004

Data Comparisons with Regulatory Guide 1.109

- **Comparison of Transfer Coefficients for ^{14}C**
  - Canadian Standards Association
  - German Regulatory Authority
  - Others
  - Milk Generally Comparable(some less than 1.109)
  - Meat & Eggs Slightly Less
- Annual Intake (Usage) of Various Food Stuffs
  - Trends From US Department of Agriculture

Case Studies PWR 1

– Collard Greens (Late July to September 24, 2012)

Sample Location & Number	Location Description	Percent Modern Carbon (pMc)	Specific Activity (pCi/ kg of Carbon)
A-1	Indicator Garden	103.2±.3	6256
B-1	Control Garden	104.6±.3	6341
C-1	Indicator Garden	104.2±.3	6317

– No Detectable Contribution Attributed to the Station

Case Studies PWR 2

Date	Vegetation	Plant Mass that is Natural Carbon	Concentration		
			Indicator	Control	Attributed to Plant
11/2011	Peppers	0.030	189.7	188.1	1.6
11/2011	Potatoes	0.103	656.9	643.0	13.9
9/2012	Potatoes	0.103	651.4	645.8	6.4
9/2012	Corn	0.120	755.6	749.2	6.4
9/2012	Potatoes	0.103	648.6	645.8	2.8
9/2012	Corn	0.120	762.1	749.2	12.9

- Concentration Units pCi/kg Fresh Sample

Case Studies (C-14 Ingestion Doses*)

- PWR 1
  - None Measurable
- PWR 2
  - Child Bone Dose From Fresh Produce
  - 2.9E-3 to 2.5E-2 mrem

*Using Equation 13 Regulatory Guide 1.109

Equation C-8 Regulatory Guide 1.109

$$C_{14}^{V}(r,\Theta) = 3.17 \times 10^{7} p Q_{14} \left[\frac{X}{Q}\right](r,\Theta) 0.11/0.16$$

- $C_{14}^{V}(r,\Theta)$ is the concentration of carbon-14 in vegetation grown at location (r,Θ) in pCi/kg
- Q_{14} is the annual release rate of carbon-14 in Ci/yr, Note that "C-14 is assumed to be released in oxide form (CO or CO_2)"
- 0.11 is the total plant mass that is natural carbon, dimensionless
- 0.16 is equal to the concentration of natural carbon in the atmosphere (gC/m^3),
- 3.17×10^7 is equal to (1.0×10^{12} pCi/Ci)(1.0×10^3 g/kg)/(3.15×10^7 sec/yr)
- p is the fractional equilibrium ratio, dimensionless

Advances in Information & Technology

- Concentration of Natural Carbon in the Atmosphere
  - .16 gC/m^3 in Regulatory Guide 1.109 (1977)
  - Currently .20 gC/m^3 (2010)*
  - The CO_2 in the Atmosphere is on an Increasing Trend
- Total Plant Mass that is Natural Carbon
  - .11 in Regulatory Guide 1.109 (1977)
  - Based IAEA Report #472* A Sampling by Vegetation Types
    - Leafy and Non-Leafy Vegetables .030
    - Root Crops .046
    - Fruit .062
    - Tubers .103
    - Sweet Corn .120
    - Feed Corn .380
    - Cereals .390
    - Leguminous Vegetables (Seed) .410

* Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments, Report 472 (IAEA, 2012)

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