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LEAF TECHNICAL GUIDANCE SERIES FOR THE DEVELOPMENT OF A NATIONAL OR SUBNATIONAL FOREST MONITORING SYSTEM FOR REDD+

Module EF-D: Emission Factors for Deforestation

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Module EF-D: Emission Factors for Deforestation

Winrock International

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	An example
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1. SCOPE

This module describes the steps necessary to create emission factors (EF) for deforestation using existing carbon stock data. The output of this module is one component of a national or subnational forest monitoring system for REDD+.

An EF is an estimate of the change in carbon stocks in all carbon pools impacted by the land use change. Emissions resulting from deforestation are usually expressed on the emissions per unit area of change, e.g., tonnes of carbon dioxide per hectare (t CO_2e ha^{-1}).

2. APPLICABILITY

The module is applicable for estimating gross and net emissions per unit of activity resulting directly from the conversion of forests to non-forest land classes.

3. PRODUCTS

This module provides the methods and procedures to estimate EFs for deforestation by cause (or driver) and by stratum using the generic IPCC methods for land converted to a new land-use category, and the IPCC[1] methods for specific types of land-use conversions from forests. All carbon pools will be included and the EFs are calculated based on the IPCC stock-difference approach (see Section 5).

[1] 2006 AFOLU Guidelines

Users of this module will be able to produce all relevant emission factors for forests converted to non-forest land uses. These emission factors are then combined with activity data (as described in Module AD-D) to develop an estimate of the emissions from deforestation (Module EM-H). Use of AD from an historical period will result in emissions that can be used to develop a reference level and use of AD and EF from long-term monitoring will feed into the MRV system.

4. REQUIRED INPUTS

EFs are based on the field data collected from implementing the sampling plan and other factors and guidance in the IPCC (2006) AFOLU Guidelines for a National GHG Inventory.

To complete this module the following data must have been previously developed:

- Forest carbon strata and non-forest strata[2]
- Carbon stock estimates (mean and uncertainty) for all included carbon pools for each forest carbon strata and each non-forest carbon strata[3]
- Quantity and purpose of timber products removed from the forest prior to clearing

[2] For methods on stratification see: Pearson, T. et al. 2013. Guidelines for Stratification for REDD+ Using a National Inventory. An additional set of guidelines for stratification when there is no existing national inventory is forthcoming.

[3] For methods on field data collection see: Walker, SM, TRH Pearson, FM Casarim, N Harris, S Petrova, A Grais, E Swails, M Netzer, KM Goslee and S Brown. 2012. Standard Operating Procedures for Terrestrial Carbon Measurement: Version 2012. Winrock International

For methods on calculations needed to estimate carbon stocks see: Module C-CS, Calculations for Estimating Carbon Stocks

5. METHODS AND PROCEDURES

EFs from deforestation must be developed for each relevant stratum and by driver or cause of deforestation (e.g. conversion to cropland, conversion to mining). These EFs are estimated following the elements outlined in Figure 1 and described in detail in this module.

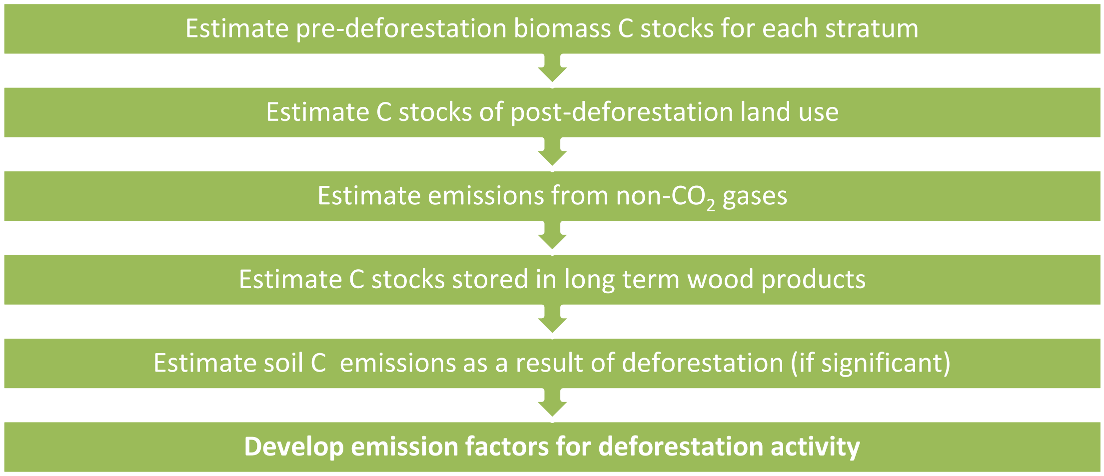

Figure 1. Required elements in the development of deforestation emission factors

Under the stock-difference[4] method, C emissions are estimated as the difference in carbon stocks before deforestation and the carbon stocks following deforestation, including carbon in living and dead biomass, carbon stored in harvested wood products, carbon released from the soil, and emissions of non-CO_2 gases. The emission factor is calculated using Equation 1:

$$EF_{def(t,x,y)} = (C_{bio.pre(x)} - C_{bio.post(t,y)} - C_{wp} + \Delta SOC_{(t)}) * 44/12 + L_{fire} \qquad \text{Eq. 1}$$

Where:

$EF_{def(t,x,y)}$ = Emission factor for year t for deforestation for stratum *x* and driver *y*, $tCO_2e\ ha^{-1}$
$C_{bio.pre(x)}$ = Carbon stock in biomass in stratum *x,* prior to deforestation, $t\ C\ ha^{-1}$
$C_{bio.post(t,y)}$ = Carbon stock in biomass in year t post-deforestation, for driver *y*, $t\ C\ ha^{-1}$
C_{wp} = Carbon stock in long-term harvested wood products following deforestation, $t\ C\ ha^{-1}$
$\Delta SOC_{(t)}$ = Change in soil carbon stocks in year t following deforestation, $t\ C\ ha^{-1}$
44/12 = Conversion factor from carbon to CO_2
L_{fire} = Emissions from burning, including non-CO_2 gases such as methane and nitrous oxide, expressed in CO_2 equivalents, $tCO_2e\ ha^{-1}$

The remainder of this module will describe how to achieve the elements in the above equation, each represented by a box in Figure 1.

[4] 2006 AFOLU Guidelines, Chapter 2 Generic Methodologies Applicable to Multiple Land-Use Categories, http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_02_Ch2_Generic.pdf

Boundaries and Time

The methods described in this module do not account for emissions that occur from post-deforestation land uses. Such emissions are outside of the accounting boundary and are assumed to be accounted for in the appropriate sector. Where emissions result directly from deforestation but occur incrementally rather than immediately (e.g. decomposition of wood products), they are calculated over an appropriate time period or treated conservatively.

A. Estimate pre-deforestation biomass carbon stocks for each stratum

The total biomass carbon stock for each stratum is the sum of all carbon stocks from measured pools (Equation 2), excluding soil carbon pool, which is reported separately.

$$C_{bio.pre(x)} = (C_{agb(x)}+C_{bgb(x)}+C_{dw(x)}+C_{lit(x)}+C_{veg(x)}) \quad \text{Eq.2}$$

Where:

$C_{bio.pre(x)}$ = Carbon stock in biomass in stratum *x*, prior to deforestation, t C ha^{-1}

$C_{agb(x)}$ = Carbon stock in aboveground live tree biomass in stratum *x*, t C ha^{-1}

$C_{bgb(x)}$ = Carbon stock in belowground live tree biomass in stratum *x*, t C ha^{-1}

$C_{dw(x)}$ = Carbon stock in deadwood pools in stratum *x*, t C ha^{-1} (includes both standing and lying deadwood)

$C_{lit(x)}$ = Carbon stock in litter in stratum *x*, t C ha^{-1}

$C_{veg(x)}$ = Carbon stock in non-tree vegetation in stratum *x*, t C ha^{-1} (includes shrubs, sapling, and herbaceous understory)

Excluded pools can be counted as zero.

A Tier 1 estimate of total uncertainty uses simple error propagation (Equation 3 for adding or subtracting uncertainties). A Tier 2/3 estimate of uncertainty uses Monte Carlo analysis, which is described in a forthcoming data analysis module.

$$U_{total} = \frac{\sqrt{(U_1 * x_1)^2 + (U_2 * x_2)^2 + \cdots + (U_n * x_n)^2}}{|x_1 + x_2 + \cdots + x_n|} \quad \text{Eq.3}$$

Where:

U_{total} = the percentage uncertainty in the sum of the quantities

x_i U_i = the uncertain quantities (mean in each pool) and the percentage uncertainties (95% confidence interval as a percent of the mean) associated with them, respectively

A module addressing data analysis and uncertainty calculations in more depth is forthcoming, and will provide calculations for uncertainty of each pool, as well as Monte Carlo analysis.

As an example, the forest carbon stocks (with percent uncertainty) in each pool in moist tropical lowland unlogged forest in country A are as follows:

$C_{agb(x)}$ = 170.6 (±9.2%) t C ha^{-1}
$C_{bgb(x)}$ = 40.1 (±9.2%) t C ha^{-1}
$C_{dw(x)}$ = 11.5 (±19.8%) t C ha^{-1}
$C_{lit(x)}$ = 1.9 (±50.1%) t C ha^{-1}
$C_{veg(x)}$ = 3.8 (±34.4%) t C ha^{-1}

Therefore, the total carbon stocks are calculated as:

$\mathbf{C_{bio.pre(x)}}$ = 170.6 + 40.1 + 11.5 + 1.9 + 23.8 = **227.9 t C ha^{-1}**

Tier 1[5] total uncertainty is calculated as:

$$\frac{\sqrt{(9.2\% * 170.6)^2 + (9.2\% * 40.1)^2 + (19.8\% * 11.5)^2 + (50.1\% * 1.9)^2 + (34.4\% * 3.8)^2}}{|170.6 + 40.1 + 11.5 + 1.9 + 3.8|} = \mathbf{7.3}\%$$

B. Estimate biomass carbon stocks of post-deforestation land use

In implementing REDD, each country must identify the type of post-deforestation land use(s), any land use cycle lengths (e.g. mean crop-fallow length, timber rotation), and determine an appropriate and defensible method to follow[6].

Equation 4 is appropriate for estimating post-deforestation biomass carbon stocks, although the tree biomass pool will often be zero. For post-deforestation land uses that have significant perennial and/or woody vegetation, it is recommended to use areas that reflect the projected post-deforestation land use, and conduct fieldwork to estimate carbon stocks of those land uses for use in estimating emission factors.

$$C_{bio.post(y,t)} = (C_{agb(y)}+C_{bgb(y,t)}+C_{dw(y)}+C_{lit(y)}+C_{veg(y)}) \qquad \text{Eq.4}$$

Where:

$C_{bio.post(y,t)}$ = Carbon stock in biomass in land use y at time t, post-deforestation, t C ha^{-1}
$C_{agb(y)}$ = Carbon stock in aboveground live tree biomass in land use y, t C ha^{-1}
$C_{bgb(y,t)}$ = Carbon stock in belowground live tree biomass in land use y at time t[7], t C ha^{-1}
$C_{dw(y)}$ = Carbon stock in deadwood pools in land use y, t C ha^{-1} (includes both standing and lying deadwood)

[5] For the sake of simplicity, Tier 1 uncertainty calculations are used in the examples within this module. However, it is recommended that Tier 2 uncertainty estimates be used whenever possible.

[6] There are currently no UNFCCC required methods that must be followed to obtain post-deforestation carbon stocks.

[7] If roots remain following deforestation, pre-deforestation belowground carbon stocks are assumed to decompose over 10 years. Therefore post-deforestation below-ground carbon stocks are estimated as $C_{bgb(x,t-1)} - (C_{bgb(x)}/10)$, where t equals years following deforestation.

$C_{lit(y)}$ = Carbon stock in litter in land use y, t C ha^{-1}

$C_{veg(y)}$ = Carbon stock in non-tree vegetation in land use y, t C ha^{-1} (includes shrubs, sapling, and herbaceous understory)

If the post deforestation land-use is cyclical, as in the case of plantations or shifting agriculture, an approach commonly used is to estimate the carbon stocks as a time-weighted average of stocks in the cycle, particularly if the cycle is relatively short (≤10 years). For land uses that accumulate biomass, but are not cyclical, such as grasslands, carbon stocks may be assumed to be the mature stocks of the post-deforestation land use.

Where there is no woody vegetation, the post-deforestation carbon stocks can be based on default values, e.g. IPCC defaults, according to the post deforestation land use. Often the post deforestation carbon stocks in all vegetation pools are estimated to be zero for post deforestation land use classes such as annual croplands, mining areas, settlements, and roads. These defaults represent a Tier I approach under IPCC and it is therefore good practice to use national data for a Tier 2 or Tier 3 approach where possible.

Further guidance on default values for post deforestation carbon stocks based on land use and calculation of post deforestation carbon stocks for a Tier 2 or Tier 3 approach can be found in the 2006 IPCC AFOLU Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use. Default values based on land use are provided in the appropriate chapters available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html.

As an example, if the post-deforestation land use is annual cropland (crop), the default biomass carbon stocks and uncertainty in country A after one year of growth are as follows, based on 2006 IPCC Guidelines, Vol. 4, Ch. 5, Table 5.9:

$\mathbf{C_{veg(\mathit{crop})}}$ = **5.0 (±75%) t C ha^{-1}**

C. Estimate non-CO_2 emissions

Emissions from non-CO_2 gases in post-deforestation land uses result from fire, drainage of forested wetlands, and agricultural activities such as fertilizer application and grazing. This module is intended for estimating gross and net emissions per unit of activity resulting **directly** from the conversion of forests to other land uses. Therefore, the boundary is defined as the emissions occurring directly following conversion from forest to non-forest, and does not include emissions associated with the on-going activities following conversion; it is assumed that those will be addressed by other sectors.[8]

[8] This is an arbitrary distinction, and may be revised in the future. In addition, it is important to note that emissions from the long-term change in biomass are still considered to fall within this boundary.

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use provide guidance on accounting for emissions of such non-CO_2 gases. An overview of non-CO_2 emission estimation is provided in Chapter 2, section 2.2.2, with references to other relevant sections.

For example, directly following deforestation, remaining biomass is often burned in preparation for the land use following conversion. The emission factor for fire, based on Equation 2.27 from the 2006 IPCC Guidelines for National GHG Inventories, is estimated as follows:

$$L_{fire} = M_B * C_f * G_{ef} * 10^{-3} \qquad \text{Eq.5}$$

Where:

- L_{fire} = amount of greenhouse gas emissions from fire, t ha^{-1} of each GHG e.g., CO_2, CH_4, N_2O.
- M_B = mass of fuel available for combustion, t dry matter ha^{-1}. This includes aboveground biomass, ground litter and deadwood. (If not directly available, this can be estimated as t C ha^{-1} * 2.)
- C_f = combustion factor, dimensionless (default values in IPCC AFOLU GL Table 2.6[9])
- G_{ef} = emission factor, g kg-1 dry matter burnt (default values in IPCC AFOLU GL Table 2.5[9])

These are converted to carbon dioxide equivalents by multiplying by the appropriate global warming potential factor (21 for methane and 310 for nitrous oxide).

As an example, assuming the land was cleared by burning, the following factors are used:

- M_B = $(C_{agb(x)} + C_{dw(x)} + C_{lit(x)} + C_{veg(x)} +)*2$ = (170.6 + 1.9 + 11.5 + 3.8) * 2 = 375.6
- C_f = 0.36 (default value for all primary tropical forests, from IPCC GL Table 2.6)
- G_{ef} = 1580 for CO_2, 6.8 for CH_4, and 0.20 for N_2O (default values for tropical forest, from IPCC GL Table 2.5)

Therefore emissions from fire are calculated as follows:

$\boldsymbol{L_{fire}}$	$CH_4 = 375.6*0.36*6.8*10^{-3}$	= 0.9 * 21	= 19.3
	$N_2O = 375.6*0.36*0.2*10^{-3}$	= 0.03 * 310	= 8.4
	Total emissions:		= **27.7 t CO_2e ha^{-1}**

Uncertainty is assumed to be 75%, due to use of default factors.

D. Estimate carbon stocks stored as wood products

[9] http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_02_Ch2_Generic.pdf

When trees removed during deforestation result in milled timber or exported logs, the carbon stocks stored in wood products following harvest, C_{wp}, are based on the efficiency of wood production, or the fraction of biomass effectively emitted to the atmosphere during production. This varies by wood product, location, and mill. It is therefore highly recommended that specific values be obtained for individual countries based on the country's mill efficiency and the proportion of specific wood products. In the absence of a country-specific value, it is recommended that a literature search be conducted to identify an appropriate figure. Alternately, a common conservative assumption is an overall efficiency of 50%.

Once obtained, the efficiency factors are multiplied by the volume that goes to each wood product class and the wood density:

$$C_{wp} = \sum (Vol_{wpc} * WD * EF_{wpc}) * 0.47 \qquad \text{Eq.6}$$

Where:

C_{wp}	= Carbon stock in wood products following deforestation, t C ha^{-1}
Vol_{wpc}	= Volume harvested (m^3/ha) by wood product class
WD	= Density of harvested wood (dimensionless)
EF_{wpc}	= Efficiency factor by wood product class (default of 50%, or justified by citation)
0.47	= carbon fraction

The method used here is conservative for wood products from deforestation. A less conservative, but more thorough accounting method would include a decay rate for wood products over time. This is briefly described in Appendix A.

For fuelwood and hand-milled timber 100% immediate emissions are assumed.

As an example, if deforestation results in a harvest of 15m^3/ha roundwood, with a wood density of 0.6, using the default efficiency factor the carbon stock stored in wood products is equal to:

C_{wp} = 15 * 0.6 *0.5 * 0.47 = **2.1 t C ha^{-1}**

Uncertainty is assumed to be 75%, due to use of default factors.

E. Determine soil carbon emitted as a result of deforestation

Changes in soil carbon stocks are related to the post deforestation land use, and it is recommended that the changes be estimated using the IPCC 2006 guidelines for this process. This IPCC method estimates the changes in soil carbon stocks based on the use of soil factors that account for how the soil is tilled, the method of management, and inputs in the post deforestation land use.

$$\Delta SOC = C_{soil} - (C_{soil} * F_{LU} * F_{MG} * F_{I}) \qquad \text{Eq.7}$$

Where:

ΔSOC = Soil carbon emitted, t C ha^{-1}

C_{soil} = Carbon stock in soil organic matter pool (to 30 cm); t C ha^{-1}

F_{LU} = Stock change factor for land-use systems for a particular land-use, dimensionless (IPCC AFOLU GL)

F_{MG} = Stock change factor for management regime, dimensionless (IPCC AFOLU GL)

F_{I} = Stock change factor for input of organic matter, dimensionless (IPCC AFOLU GL)

The change in soil carbon stocks is assumed to occur over a 20 year time period, at which time a new steady state for a given land use is reached. To account for this time period, $\Delta SOC_{(t)}$, as used in Equation 1, is estimated as ΔSOC / 20 for the first 20 years, and 0 thereafter.

Additional guidance on estimating change on soil carbon, suggested default time periods, and additional soil carbon factors can be found in in the 2006 IPCC AFOLU Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use.[10]

As an example, with hypothetical soil carbon stocks of 102 t C ha^{-1}, the moist tropical lowland forest in country A, converted to cropland uses the following IPCC soil carbon factors:

F_{LU}: 0.48
F_{MG}: 1.00
F_{I}: 1.00

And therefore has the following soil carbon emissions:

$\boldsymbol{\Delta SOC}$ = 102 – (102 * 0.48 * 1.00 * 1.00) = 53.0 t C ha^{-1}

This must be divided by 20 to estimate annual change in soil carbon: **8.4** t C ha^{-1}
Uncertainty is assumed to be 75%, due to use of default factors.

F. Create emission factors for deforestation activity

After all of the individual elements have been calculated, Equation 1 can now be applied:

$$EF_{def(t,x,y)} = (C_{bio.pre(x)} - C_{bio.post(t,y)} - C_{wp} + \Delta SOC_{(t)}) * 44/12 + L_{fire} \qquad \text{Eq. 8}$$

Combining all of the factors calculated in examples used in previous steps, the EF for the moist tropical lowland forest for country A is calculated as follows:

$$EF_{def(1,A,cropland)} = (227.9 - 5.0 - 2.1 + 8.4) * 44/12 + 27.7 = \mathbf{868.1\ tCO_2e\ ha^{-1}}$$

[10] IPCC (2006). Guidelines for National Greenhouse Gas Inventories. Volume 4, Agriculture, Forestry and Other Land Use. For soil carbon factors, see relevant chapters for post-deforestation land use: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

Uncertainty is calculated as described in Equation 3 (all factors converted to $tCO_2e\ ha^{-1}$):

$$\frac{\sqrt{(7.3\% * 835.6)^2 + (75\% * 18.3)^2 + (75\% * 7.7)^2 + (75\% * 30.8)^2 + (75\% * 27.7)^2}}{|835.6 + 18.3 + 7.7 + 30.8 + 241.3|} = \mathbf{7.6\%}$$

The end goal is to develop an emission factor look up table as in the example in table 3 below.

Table 3. Example of a look up table demonstrating emission factors (and uncertainties) for various deforestation scenarios.

From	To	
	Bare land	Cropland
	$t\ CO_2e/ha$	
Carbon stratum A	975 (13.2%)	**868 (7.6%)**
Carbon stratum B	450 (11.9%)	400 (13.0%)
Carbon stratum C	800 (12.2%)	760 (11.1%)
Carbon stratum D	1,050 (12.9%)	900 (12.5%)

APPENDIX A: ACCOUNTING FOR DECAY RATE OF WOOD PRODUCTS

The approach used to account for carbon stored in wood products in this module is conservative and is therefore acceptable. However, it would be more accurate to account for decay of wood products over time. The rate at which carbon is emitted from harvested wood products over time is a function of the rate of retirement of products from end uses and the various processes used to dispose of products:

- Carbon is emitted to the atmosphere when the product is retired and disposed of. How much is emitted and when is controlled by:
  - Carbon may be immediately emitted to the atmosphere through burning of wood products;
  - If wood products are burned for energy production, the carbon is emitted but the energy produced will displace some fossil fuel emissions that therefore remain in storage, resulting in emission reductions;
  - Retired wood products may also be recycled, extending the duration of carbon storage in end uses; and
  - When retired products are landfilled, the rate of decomposition is extremely slow and a proportion of carbon in the product is considered to be stored indefinitely.

The IPCC Tier 1 method uses default data and assumes a first order decay function for the in-use lifetime of products. Change in carbon stocks in in-use products may be estimated using the following equation, adapted from IPCC:

(A) $$C_{wp}(i+1) = e^{-k} * C_{wp}(i) + \left[\frac{(1-e^{-k})}{k}\right] * Inflow(i)$$ Eq.5

(B) $$\Delta C_{wp}(i) = C_{wp}(i+1) - C_{wp}(i)$$ Eq.6

Where:

i = year

$C_{wp}(i)$ = the carbon stock of the Harvested Wood Products (HWP) pool in the beginning of year *i*, t C

k = decay constant of first-order decay given in units, yr^{-1} (*k*=ln(2)/HL, where HL is half-life of the HWP pool in years. A half-life is the number of years it takes to lose one-half of the material currently in the pool.)

Inflow(*i*) = the inflow to the HWP pool during year *i*, t C yr^{-1}

$\Delta C_{wp}(i)$ = carbon stock change of the HWP pool during year *i*, t C yr^{-1}

Tier 2 requires using country-specific data, and Tier 3 entails developing a detailed, country-specific method to estimate relevant variables that may include use of a decay function other than first order decay.

More information is available from the IPCC 2006 Guidance for National Greenhouse Gas Inventories (Volume 4, Chapter 12)[11].

[11] http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_12_Ch12_HWP.pdf

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