

A Healthy Diet for a Growing Population: A Case Study of Arua, Uganda

Appendix B - Linear Programming Model Formulation

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M.I. Hermelink^{1,*}, K.H. Pittore², A. Alvarez Aranguiz³, F.I.
Pereira da Silva⁴, M.M.I. Roefs², R. Kajobe⁵, R. Maligumu⁵, and
H. Hengsdijk¹

¹ *Wageningen Plant Research, Droevendaalsesteeg 1, 6708 PB, Wageningen, The Netherlands*

² *Wageningen Centre for Development Innovation, Droevendaalsesteeg 1, 6708 PB, Wageningen, The Netherlands*

³ *Wageningen Livestock Research, De Elst 1, 6708 WD, Wageningen, The Netherlands*

⁴ *Wageningen Food & Biobased Research, Bornse Weilanden 9, 6708 WG, Wageningen, The Netherlands*

⁵ *Muni University, P.O. Box 725, Arua, Uganda*

* *Corresponding author: M.I. (Marleen) Hermelink, marleen.hermelink@wur.nl*

1 Appendix B1 - Model Symbols

Table 1: Symbol definitions for the linear programming model in Appendix B2

Symbol	Unit(s)	Definition
Sets		
i	-	Cropping system
p	-	Crop
j	-	Food product
k	-	Food group
z	-	Human nutrient
e	-	Animal nutrient
a	-	Animal type
t	-	Growing Season

Objective Value

A	ha	Agricultural area i
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Decision Variables

x_i	ha	Area of cropping system i
l_a	-	Number of animals of type a
r_{pa}	kg/y	Amount of crop residue of crop p fed to animal type a
f_{ja}	kg/y	Amount of edible part of product j fed to animal type a
q_{ja}	kg/y	Amount of non-edible part of product j fed to animal type a
h_j	kg/y	Amount of edible part of product j consumed by humans
d_j	kg/y	Amount of edible part of product j discarded

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Symbol	Unit(s)	Description
Parameters		
Y_{jp}	kg/ha/s	Yield (per season) of product j from crop p
X_p	kg/ha/s	Yield (per season) of crop residues from crop p
Z_{ja}	kg/a/y	Yield (per year) of product j from animal type a
B_{pit}	1/0	Is crop p produced in cropping system i in season t ? (binary)
P_{jk}	1/0	Does product j belong to food group k ? (binary: 1=yes, 0=no)
G_k, G_k^+	kg/y	Min & max yearly intake of food group k of whole population
C_{zj}	kcal/kg	Content of human nutrient z in product j per kg in harvest conditions
	g prot/kg	
	mg Iron/kg	
	μ g RAE/kg	
N_z^-	kcal/y	Min yearly intake of human nutrient z of whole population
	g prot/y	
	mg Iron/y	
	μ g RAE/y	
L_j	frac.	Fraction lost of product j in supply chain
E_j	frac.	Edible fraction of product j
D_p	kg DM/kg	Dry matter content of crop residue of crop p in harvest conditions
$D_{h''}$	kg DM/kg	Dry matter content of edible part of product j in harvest conditions
$D_{j_{h''}}$	kg DM/kg	Dry matter content of non-edible part of product j in harvest conditions
M_a	kg DM/a/y	Min yearly dry matter intake for animal type a
S_{pa}'	1/0	Residues of crop p suitable for animal type a ? (binary: 1=yes, 0=no)
S_{ja}''	1/0	Edible part of product j suitable for animal type a ? (binary: 1=yes, 0=no)

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Symbol	Unit(s)	Description
S'''_a	1/0	Non-edible part of product j suitable for animal type a ? (binary: 1=yes, 0=no)
T'_{epa}	MJ ME/kg DM kg CP/kg DM Fibrous DM? 1/0	Content of animal nutrient e in residue of crop p for animal type a
T''_{eja}	See T'_{epa}	Content of animal nutrient e in edible part of product j for animal type a
T'''_{eja}	See T'_{epa}	Content of animal nutrient e in non-edible part of product j for animal type a
V_{ea}^+, V_{ea}^-	MJ ME/a/y kg CP/a/y kg fibrous DM/a/y	Min & max intake per animal unit of nutrient e by animal type a

2 Appendix B2 - Model Formulation

Objective Function: $\min_{x_i} \left\{ A = \sum_i x_i \right\}$

Subject to:

Production:

Crop Res. Produced: $\sum_{i,t} x_i X_p B_{pit} = R_p \quad \forall p$

Food Produced: $\sum_{i,p,t} x_i Y_{jp} B_{pit} (1 - L_j) E_j + l_a Z_{ja} = F_j \quad \forall j$

Non-Edible Produced: $\frac{F_j}{E_j} (1 - E_j) = Q_j \quad \forall j$

Food for Pop.: $F_j - \sum_a f_{ja} - d_j = h_j \quad \forall j$

Healthy Diet:

Food Group Intake: $G_k^- \leq \sum_j h_j P_{jk} \leq G_k^- \quad \forall k$

Nutrient Intake: $\sum_j h_j C_{zj} \geq N_z \quad \forall z$

Feed Availability:

Crop Residue: $\sum_a r_{pa} \leq R_p \quad \forall p$

Edible Frac.: $\sum_a f_{ja} \leq F_j \quad \forall j$

Non-Edible Frac.: $\sum_a q_{ja} \leq Q_j \quad \forall j$

Feed Requirements:

DM Intake: $\sum_p r_{pa} D'_p S'_{pa} + \sum_j (f_{ja} D''_j S''_{ja} + q_{ja} D'''_j S'''_{ja}) \leq l_a M_a \quad \forall a$

Nutrient Intake: $l_a V_{ea}^- \leq \sum_p r_{pa} D'_p T'_{epa} S'_{pa} + \sum_j (f_{ja} D''_j T''_{eja} S''_{ja} + q_{ja} D'''_j T'''_{eja} S'''_{ja}) \leq l_a V_{ea}^+ \quad \forall a$

$x_i, l_a, r_{pa}, f_{ja}, q_{ja}, h_j, d_j \geq 0$

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3 Appendix B3: Decision Sets

Table 2: Set lists of crops (i), food products (j), food groups (k), human nutrients (z), animal nutrients (e), and growing seasons (t) used in the LP model.

*Grass is included as a food product but has an edible fraction of 0.

p	Crop	j	Food Product	k	Food Group
1	maize	1	maize	1	cereals
2	sorghum	2	sorghum	2	eggs
3	cassava	3	cassava root	3	fruits
		4	cassava leaves	4	vegetables
4	sweet potato	5	sweet potato root	5	meat
		6	sweet potato leaves	6	dairy
5	plantain	7	plantain	7	oils
6	mango	8	mango	8	legumes
7	banana	9	banana	9	tubers
8	papaya	10	papaya		
9	beans	11	beans	z	Human Nutrient
10	pigeon pea	12	pigeon pea	1	calories
11	soybeans	13	soybeans	2	proteins
12	sesame	14	sesame	3	Iron
13	groundnuts	15	groundnuts	4	vitamin A
14	tomato	16	tomato		
15	cabbage	17	cabbage	e	Animal Nutrient
16	onion	18	onion	1	metabolizable energy
17	pumpkin	19	pumpkin flesh	2	crude protein
		20	pumpkin seeds	3	fibrous dry matter
		21	pumpkin leaves		
18	eggplant	22	eggplant	t	Growing Season
19	sugarcane	23	sugarcane stalks	1	season 1 (Mar-May)
20	grass	24	grass*	2	season 2 (Aug-Dec)
a	Animal Type	j	Food Product		
1	dairy cattle	25	beef		
		26	milk		
3	beef cattle	25	beef		
4	goats	27	goat meat		
5	chicken	28	chicken meat		
		29	eggs		

Table 3: Set list of cropping systems (i) included in the LP model, with the first crop grown in season 1 (Mar-May, $t = 1$) and the second in season 2 (Aug-Dec, $t = 2$). *Grass is included amongst the cropping systems as permanent grassland, with grass in both seasons, but its harvested product has an edible fraction of 0.

i	Cropping system
1	maize - maize
2	maize - sorghum
3	maize - sweet potato
4	maize - potato
5	maize - beans
6	maize - pigeon pea
7	maize - soybeans
8	maize - sesame
9	maize - groundnuts
10	maize - tomato
11	maize - cabbage
12	maize - onion
13	maize - pumpkin
14	maize - eggplant
15	sorghum - sorghum
16	sorghum - sweet potato
17	sorghum - potato
18	sorghum - beans
19	sorghum - pigeon pea
20	sorghum - soybeans
21	sorghum - sesame
22	sorghum - groundnuts
23	sorghum - tomato
24	sorghum - cabbage
25	sorghum - onion
26	sorghum - pumpkin
27	sorghum - eggplant
28	sweet potato - sweet potato
29	sweet potato - potato
30	sweet potato - beans
31	sweet potato - pigeon pea
32	sweet potato - soybeans
33	sweet potato - sesame
34	sweet potato - groundnuts
35	sweet potato - tomato
36	sweet potato - cabbage

i	Cropping system
37	sweet potato - onion
38	sweet potato - pumpkin
39	sweet potato - eggplant
40	beans - pigeon pea
41	beans - soybeans
42	beans - sesame
43	beans - groundnuts
44	beans - tomato
45	beans - cabbage
46	beans - onion
47	beans - pumpkin
48	beans - eggplant
49	pigeon pea - soybeans
50	pigeon pea - sesame
51	pigeon pea - groundnuts
52	pigeon pea - tomato
53	pigeon pea - cabbage
54	pigeon pea - onion
55	pigeon pea - pumpkin
56	pigeon pea - eggplant
57	soybeans - sesame
58	soybeans - groundnuts
59	soybeans - tomato
60	soybeans - cabbage
61	soybeans - onion
62	soybeans - pumpkin
63	soybeans - eggplant
64	groundnuts - groundnuts
65	groundnuts - tomato
66	groundnuts - cabbage
67	groundnuts - onion
68	groundnuts - pumpkin
69	groundnuts - eggplant
70	sugarcane - sugarcane
71	mango - mango
72	banana - banana
73	papaya - papaya
74	cassava - cassava
75	plantain - plantain
76	grass - grass*