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► **To cite this version:**

Kevin Morel, Magali San Cristobal, Francois Leger Léger. Simulating incomes of radical organic farms with MERLIN: A grounded modelling approach for French microfarms. *Agricultural Systems*, 2018, 161, pp.89-101. 10.1016/j.agsy.2017.08.006 . hal-02939224

HAL Id: hal-02939224

<https://hal.inrae.fr/hal-02939224>

Submitted on 15 Sep 2020

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1 **Simulating incomes of radical organic farms with MERLIN: A** 2 **grounded modeling approach for French microfarms**

3 **Abstract**

4 Microfarms are commercial soil-based market gardens that cultivate less than 1.5 ha of
5 organic vegetables per farmer in rural France. They seek to make a living on small acreage by
6 using innovative strategies that combine high land-use intensity with low input and few
7 mechanized practices, and directly sell a wide range of vegetables. Few academic studies have
8 focused on microfarms. Our research objective was to build a simulation model of microfarms
9 income and agricultural area based on farmers' expertise. The originality of our approach that
10 we coined as "grounded modeling" (Glaser and Strauss, 2009) was to implement an interactive
11 development pipeline based on inductive qualitative analysis and farmers' participation to
12 collect data, build and validate a model adapted to the specificity of microfarms, rather than
13 using pre-existing models. Based on extensive data collection and interactions with 20
14 microfarms, we built a stochastic simulation model (MERLIN) at the farm level, which
15 combined (i) two mixed models to predict yields and workload according to farming practices
16 for 50 crops, and (ii) a crop-planning model. One major innovation of the MERLIN model is
17 to generate cropping plans that match the complex and temporal commercial requirements for
18 direct selling of vegetable boxes through community-supported agricultural schemes. The
19 model was validated based on a case-study designed with microfarmers which involved
20 different sets of strategic choices (3 technical systems, 2 marketing strategies, 3 investment
21 hypotheses), climate (mild or cold) and chosen annual workload (1,800h; 2,500h or 3,000h).
22 Our model was judged relevant and legitimate by agricultural practitioners because it was not
23 prescriptive and its simulations combined different types of strategies in accordance with a
24 global approach favored by organic farmers. Grounded modeling is a promising method to
25 create generic knowledge specifically adapted to radical organic farming systems. However,

26 the epistemological implications of grounded modeling require further investigation, which
27 may benefit from the transdisciplinary framework developed in agroecological studies.

28 **Keywords:** Agroecology; Participatory modelling; Short supply chains; Crop planning;
29 Horticulture

30 **1. Introduction**

31 The economic viability of radical organic farming systems (ROFS) has been infrequently
32 investigated. ROFS are based on the historical roots of organic agriculture, which go far beyond
33 technical issues and promote small-scale farming to maintain rural employment, alternative
34 commercial strategies such as short supply chains to foster local economies and create social
35 links between consumers, and do-it-yourself approaches to enhance the farmer's autonomy
36 (Besson, 2011).

37 Organic market gardening microfarms in France (hereafter called microfarms) are good
38 examples of ROFS. They have been characterized by Morel and Léger (2016) as commercial
39 farms that meet the following four criteria: (1) soil-based market gardening is the main income-
40 generating activity (excludes roof-top gardening, although part of the cultivated acreage can be
41 protected under cold tunnels); (2) a high level of cultivated biodiversity is grown organically,
42 with 30 to 80 vegetables and herbs (excludes mushroom and fruit production); (3) the utilized
43 agricultural area is less than 1.5 ha by full-time equivalent, which is the minimal size generally
44 recommended by French official agricultural development agencies for diversified market
45 gardening (GAB/FRAB, 2009); and (4) farmers sell their produce directly to consumers
46 primarily through vegetables boxes in community-supported agriculture (CSA) schemes where
47 customers pay one year in advance weekly vegetables boxes which are expected to contain an
48 assortment of seasonally available produce all over the productions season. Agricultural
49 teachers and extension agents have observed the growing popularity of microfarms in France,
50 first in rural areas and now also in urban areas where space is limited. No specific statistics

51 about microfarms have been collected, but a study reported that approximately one-third of
52 3,000 new farms in France were created by young people with no agricultural background
53 (Jeunes Agriculteurs, 2013). These new farmers are attracted by organic agriculture (63%),
54 short supply chains (58%), and market gardening (23%) which is the type of production
55 attracting the highest number of people.

56 Microfarmers claim that they can be economically successful despite their small size
57 (Fortier, 2014; Hervé-Gruyer and Hervé-Gruyer, 2016) thanks to a wide range of strategies
58 including low-input practices (external commercial fertilizers and phytosanitary products are
59 limited), high cropping densities, and limited mechanization. Young farmers who do not take
60 over the family farm are often very enthusiastic about microfarms because they require little
61 land and a low level of capital investment. However, the economic viability of microfarms has
62 not been evaluated by research.

63 Little data is available for ROFS, and microfarms are still atypical initiatives. This precludes
64 statistical approaches to analyze their economic viability. We assumed that computational
65 modeling and *in silico* experiments could facilitate the investigation of a wide range of ROFS
66 scenarios following a logic of *in silico* experimentation (Martin et al., 2011). A microfarm
67 model should integrate alternative marketing and investment strategies in addition to technical
68 details. Developing ROFS models is technically challenging because of the lack of fundamental
69 data and academic knowledge about their farming practices. Radical organic farmers often do
70 not trust top-down approaches, which can lead to invalidation of models generated without their
71 expertise (Cash et al., 2003).

72 Our research objective was to build and validate a simulation model of microfarms income
73 and agricultural area based on farmers' expertise. We developed a static stochastic simulation
74 model at the farm level called MERLIN (Microfarms: Exploratory Research on Labor and
75 Income), which was based on data from 20 microfarms in northern France. The originality of

76 our approach that we coined as “grounded modeling” (Glaser and Strauss, 2009) was to
77 implement an interactive development pipeline based on inductive analysis and farmers’
78 participation to collect data, build and validate a model adapted to the specificity of microfarms,
79 rather than using pre-existing models.

80 **2. Materials and methods**

81 *2.1. Overall description of the grounded modeling approach*

82 The research process ran from 2014 to 2016 and was designed investigate the question of
83 microfarms viability. In the first step described by Morel and Léger (2016), 1-day
84 comprehensive interviews were carried out on 20 microfarms to understand microfarmers’
85 objectives and practices. Qualitative inductive analysis of this material collected in 2014 (Miles
86 and Huberman, 2010) highlighted that the viability of microfarms involved both material
87 aspects (incomes, workload) and immaterial aspects (quality of life, autonomy, meaning) and
88 that 6 major strategic choices impacting microfarms viability: community integration,
89 investment, marketing, technical system, labor organization, spatial and temporal organization
90 of cultivated biodiversity. During 3 group workshops and individual discussions (for 5
91 microfarmers out of 20 who could not attend the workshops), farmers judged that it would be
92 relevant for them and future microfarmers to develop a tool for decision support focusing on
93 material aspects (incomes and workload) which raised the strongest doubts and questions
94 among them. They showed a strong interest in developing a model to simulate incomes and
95 agricultural area according to workload and contrasted strategic choices. Three types of
96 strategic choices out of 6 were considered by farmers especially relevant to investigate
97 economic aspects: technical system, marketing and investment.

98 Existing biophysical mechanistic crop models that focus primarily on cereals (Jones et al.,
99 2003; Keating et al., 2003; Brisson et al., 2004) are not suited to the broad diversity of
100 vegetables grown by microfarms. Although some information is available on the effect of low-

101 input practices on the economics of different farming systems (Pimentel et al., 1989; Clark et
102 al., 1999), the effect of low investment strategies through do-it-yourself approaches often
103 promoted by microfarmers have not been quantified. Microfarmers were really enthusiastic
104 about the possibility to run a high number of simulations in order to “take distance” from their
105 daily reality and the limited number of existing microfarms. They were interested in testing
106 different cropping plans because crop planning was perceived as a major challenge. Indeed,
107 microfarmers sell boxes of vegetables on a weekly basis, and their main objective is to provide
108 a diverse selection of produce throughout the marketing season to maximize customer loyalty.
109 Existing crop planning and land-use models optimize yields or incomes while minimizing
110 environmental impacts (Dogliotti et al., 2005; Dury et al., 2012) but these models do not
111 adequately simulate the complex and temporal commercial requirements in short supply chains
112 (Aubry et al., 2011). To develop a tool adapted to the specific needs of microfarmers, we could
113 not rely on current agronomic models. We decided to develop an original model based on the
114 expertise of microfarmers as is done in participatory modelling approaches (Voinov and
115 Bousquet, 2010).

116 To develop the conceptual architecture of MERLIN, we did not directly engage the
117 microfarmers, which deviated from some participatory modelling approaches in which tools
118 such as diagrams, cognitive maps, or software are developed that allow the stakeholders to
119 design the model (Mendoza and Prabhu, 2006; Etienne et al., 2011). Microfarmers were
120 involved in sharing their experience in 3-hours semi-structured interviews which were carried
121 out on 20 microfarms in 2014 and 2015 and that we hold as form of participation through
122 consultation (Pretty, 1995). The main themes discussed in interviews were how and in which
123 way technical system, marketing and investment could impact incomes and agricultural area.
124 The collected material was processed following a method of inductive qualitative analysis,
125 which is classic in grounded research (Glaser and Strauss, 2009), using thematic coding and
126 matrix tools described by Miles and Huberman (1984). More and more abstract categories were

127 built on the basis of an iterative cross analysis of interview content and to reveal relations
128 between these categories.

129 This analysis resulted in the conceptual architecture of MERLIN (**Fig. 1**) and showed that
130 technical system impacted yields and production workload per crop, investment impacted costs
131 and production workload (as self-building of equipment could raise workload) and that
132 agricultural area and production on the farm were linked to crop planning that was designed to
133 fulfill the specific requirements of direct-selling and the level of annual workload. To predict
134 yields and workload, mixed models were built based on farm data collected in 2016 from a
135 reduced sample of 10 microfarms (described later) due to time constraints. To simulate crop
136 planning adapted to direct selling, a specific sub-model was designed (detailed later) based on
137 cropping cycles collected on this sample and marketing criteria that were developed based on
138 farmers' expertise in a collective workshop with 3 farmers in winter 2015 and validated by all
139 microfarmers of the sample.

140 To validate the modelling outputs, we used the MERLIN model in a case-study to simulate
141 incomes and agricultural area according to different set of strategic choices, climate and chosen
142 annual workload. The modalities of input variables, including 3 possible technical systems, 2
143 marketing strategies and 3 investment hypotheses were designed with 6 farmers during a 2-
144 hours collective workshop in 2015 (and validated afterward by all farmers of the sample) to
145 represent contrasted strategic options which raised questions about economic efficiency and
146 required land among microfarmers and people interested in starting a microfarm.

147 2.2. *Conceptual architecture of the model*

148 The MERLIN model was developed at the farm level considering that the goal of the
149 farming systems was to guarantee a quantity and diversity of produce to sell throughout the
150 marketing season in a CSA scheme. Our model combined three sub-models. Sub-model 1
151 (SM1) predicted yields per unit surface area ($\text{kg}\cdot\text{m}^{-2}$) for 50 crops depending on farming
152 practices. Sub-model 2 (SM2) predicted production workload per unit surface area ($\text{h}\cdot\text{m}^{-2}$) for

153 50 crops depending on farming practices and investment strategies. Sub-model 3 (SM3)
154 generated yearly cropping plans to meet the requirements of the marketing strategy; cropping
155 plans refer to the acreage occupied by all crops every year, their temporal allocation and their
156 distribution within the farm (Dury et al., 2012). MERLIN combined these three models and the
157 other elements presented in **Fig. 1** to simulate income and agricultural area utilized for a single
158 farm according to the level of chosen annual workload.

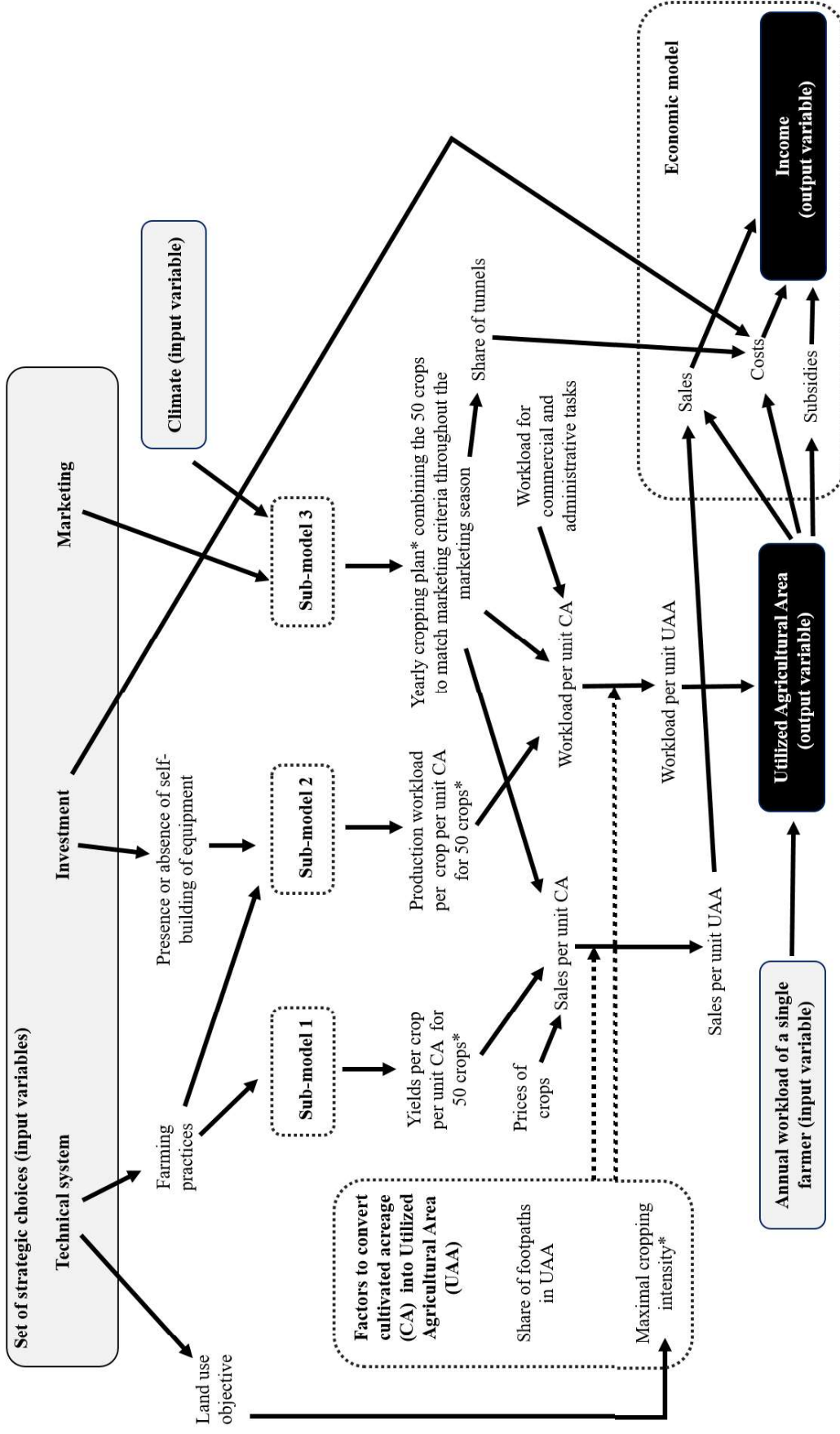


Fig. 1. Conceptual architecture of the MERLIN model. At each iteration, yields, production workload per crop, maximal cropping intensity (MCI) and cropping plan (all variables indicated by the symbol *) are drawn randomly in a range of values depending on input variables. Utilized agricultural area (UAA) and incomes are calculated based on these random values and fixed parameters according to input variables. The different sub-models and parameters are detailed later in the body of the text and tables. Cultivated acreage (CA) refers to the area of crop production excluding footpaths and not considering the possible practice of intercropping, growing green manure, and leaving land fallow between cropping cycles which vary according to the land use objective of each technical system (integrated by the MCI variable). These factors are considered to convert CA into UAA

165

166 2.3. *Data collection for model calibration*

167

168 2.3.1. *Microfarm sampling*

169 To calibrate the model, 10 microfarms were selected from among the 20 microfarms

170 involved in building the conceptual architecture of MERLIN. The 10 microfarms were selected

171 according to theoretical sampling (Eisenhardt, 1989), and ensuring that they represented

172 microfarm diversity for four farming practice variables that potentially affect yields and

173 production workload (**Table 1**). We visited each of the 10 microfarms an average of four times

174 during one year to collect data.

175 **Table 1**

176 Characteristics of the 10 microfarms used to calibrate the model.

Farming practice variables								
Farm	Region	Age of farm (yr)	UAA per full time-equivalent (m ²) *	UAA under tunnels (m ²)	Mechanization**	Low-input practices ***	Intercropping ****	Self-built equipment *****
A	Brittany	3	8,000	13%	T	Yes	Yes	No
B	Brittany	5	4,300	19%	Me	No	No	No
C	Pays de la Loire	5	8,000	10%	Me	No	No	No
D	Pays de la Loire	4	3,000	18%	M	Yes	No	No
E	Centre-Val de Loire	2	1,800	9%	M	Yes	No	Yes
F	Normandy	9	1,250	48%	M	Yes	Yes	No
G	Normandy	4	8,000	10%	Me	Yes	No	Yes
H	Lorraine	4	3,500	23%	T	Yes	No	Yes
I	Lorraine	5	8,500	18%	T	No	No	No
J	Lorraine	4	3,500	25%	T	Yes	No	No

177 * Utilized agricultural area dedicated to market gardening includes footpaths between the cropping beds but not
 178 the area dedicated to buildings or access roads. Full-time equivalent was estimated by farmers and corresponds to
 179 an average workload from 35–50 h per week.

180 ** Mechanization: M, manual labor for all farming activities including superficial tillage; T, mechanization only
 181 for tillage, mainly practiced with a tiller; Me, mechanization for most farming practices (tractor) except for some
 182 hand-harvesting.

183 *** Low-input practices: Include a variety of practices such as straw mulching, green manure, preparing farm-
 184 made phytosanitary preparations, and composting animal manure freely available from local organic or
 185 conventional cattle breeders. “Yes” means that farmers implemented as much as possible such practices to reduce
 186 the costs of commercial inputs whereas “No” means that farmers preferred generally to buy commercial inputs to
 187 make work easier and faster (results from the qualitative analysis of interviews).

188 **** Intercropping: Two to five crops are grown together and carefully chosen to have complementary heights to
 189 maximize incident light, different rooting depths to maximize water and nutrient absorption, and different
 190 maturation times to limit competition between plants (De Liedekerke De Pailhe, 2014).

191 ***** Self-built equipment: Farmers construct as many tools, equipment, and farm buildings as possible, from
 192 previously used or free materials (do-it-yourself approach).

193

194 *2.3.2. Calculating average marketable yields*195 For each farm, mean yields (Y, in kg·m⁻²) were calculated for the 50 most common crops196 grown by microfarmers (**Table 2**). We calculated marketable yields, which accounted for field

197 and storage losses, based on records kept by farmers of all sales since farm creation (aggregating

198 tunnels and outdoors areas). For crops with several harvests and sales during a cropping cycle,
199 cumulative sales were calculated to determine the total sales attached to a cropping cycle.
200 Marketable yields were calculated by dividing the sales with their corresponding cultivated
201 acreage excluding footpaths.

202

203 2.3.3. *Estimating production workload for each crop*

204 Most farmers did not have records for the workload dedicated to each crop. Therefore, we
205 estimated the average production workload per unit area of cultivated acreage (W_p , in $\text{min}\cdot\text{m}^{-2}$)
206 for each crop on each farm according to the procedure of Morel (2016; pp. 282–284), which
207 was based on farmer's expert knowledge. Farmers estimated their production workload over
208 the year considering the frequency of 'light weeks,' 'regular weeks,' and 'busy weeks.' The
209 global annual workload was then allocated to each crop based on its respective acreage and a
210 categorization made by farmers of their crops (

211 **Fig. 2**) according to the workload required ('light,' 'regular,' or 'heavy') for the three phases of
212 the production cycle (setting up, managing, and harvesting the crop).



213

214 **Fig. 2.** Farmer categorizing the workload of his crops for a specific stage of the production cycle (here, the setting-
215 up stage). Each piece of paper represents a crop that the farmer categorizes in three columns (light, regular, or
216 heavy workload) based on his expertise.

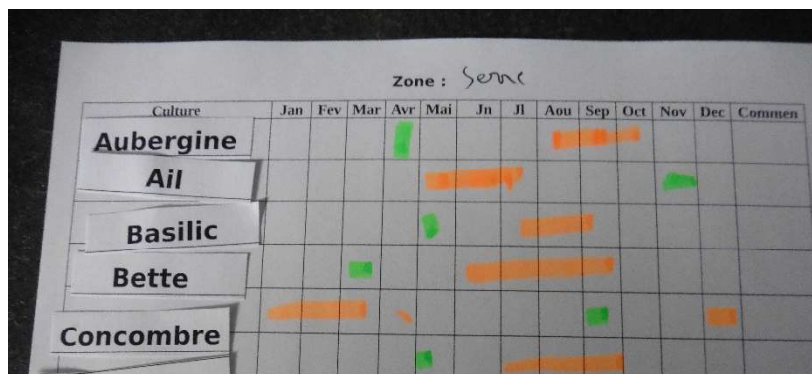
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218

219 2.3.4. *Creating a database of cropping cycles*

220 Cropping plans were generated to combine cycles of different crops over the year. A
221 cropping cycle was defined by the planting month and harvesting period (in months) for a
222 specific crop. Cropping cycles were distinguished for two locations (outside field or unheated
223 tunnels) and two climatic zones (cold or mild climate). The cold climate referred to the Lorraine
224 and Normandy areas (mean monthly minimum temperature, 0°C in winter and 13°C in summer;
225 mean monthly maximum temperature, 6.5°C in winter and 24°C in summer). The mild climate
226 referred to Brittany, Pays de La Loire, and Centre-Val de Loire (mean monthly minimum
227 temperature, 4°C in winter and 13.5°C in summer; mean monthly maximum temperature, 9°C
228 in winter and 23°C in summer). The main difference between these two climates was the length
229 of winter temperature with risk of freezing, which was an average of 6 months for the cold
230 climate and 5 months for the mild climate.

231 We collected data on cropping cycles for each farm based on existing planning documents
232 if available. Otherwise, we asked the farmer to mark a calendar with the different possible
233 cropping cycles on the farm (**Fig.3**). Then, data from the 10 microfarms was synthesized to
234 build a database of 1,053 possible cropping cycles according to all crops, locations, climates,
235 and marketing strategies (described later). These cycles are detailed in Morel (2016; pp.
236 290–317). For a given crop, climate and marketing strategy, various cropping cycles were
237 possible with different lengths according to their planting month. The number of possible
238 cropping cycles were 5.6 in average and ranged from 1 for spring garlic for example (planted
239 in November and harvested in March under tunnel in the 12-month marketing strategy and cool
240 climate) to 34 for lettuce. Indeed, lettuce growing cycles could be started every month except
241 in January, under tunnel or outside, with different growing period lengths (short cycle with one
242 harvest or longer cycle with cut-and-come-again strategies).



243
244 **Fig. 3.** Example calendar showing the cropping cycles under tunnels (“serre” in French) for a microfarm in a cold
245 climate. The left column refers to crops (eggplant, garlic, basil, chard, and cucumber). The 12 other columns refer
246 to the 12 months of the year. The planting period was drawn in green and the harvesting period in orange.

247 *2.3.5. Characterizing costs, subsidies, and prices*

248 The variable and fixed production costs attached to the different farming practices and
249 investment strategies and subsidies were averages derived from all financial documents
250 available since farm creation. The crop selling price (**Table 2**) was the average price from the
251 10 microfarms for organic vegetables sold in CSA schemes. These prices were affordable for
252 people with lower- and middle-incomes in rural areas.

253

254 **Table 2**

255 Characteristics of the 50 crops considered in the model.

Crop	Crop category	Crop share (kg)	Price (EUR·kg ⁻¹)	Effect on log (Yields)	Effect on log (Production workload)	Grown in tunnels	Grown outdoors
Beetroot (fresh)	Root crop	0.80	3.04	0.18	-0.26	Yes	Yes
Beetroot (storage)*	Root crop	0.63	2.58	0.67	-0.06	No	Yes
Broad bean	Fruit crop	1.00	4.08	-0.06	-0.16	Yes	Yes
Broccoli	Cooked greens	0.50	3.57	-1.04	-0.51	Yes	Yes
Brussels sprouts	Cooked greens	0.50	4.46	-0.66	-0.05	No	Yes
Cabbage	Cooked greens	0.81	2.47	0.53	-0.28	Yes	Yes
Carrot (fresh)	Carrot	0.58	3.37	0.42	0.17	Yes	Yes
Carrot (storage)*	Carrot	1.00	2.43	0.67	0.25	No	Yes
Cauliflower	Cooked greens	0.78	3.04	-0.82	-0.47	Yes	Yes
Celeriac (storage)*	Root crop	0.75	3.02	0.21	-0.15	Yes	Yes
Celery	Cooked greens	0.50	2.63	0.17	-0.37	Yes	Yes
Chard	Cooked greens	0.96	2.68	0.05	-0.34	Yes	Yes
Chicory	Raw greens	0.40	4.5	-0.42	-0.73	Yes	Yes
Chili	Seasoning	0.09	11.34	-1.96	-0.14	Yes	No
Chinese cabbage	Fruit crop	0.70	4.33	0.29	-0.18	Yes	Yes

Crop	Crop category	Crop share (kg)	Price (EUR·kg ⁻¹)	Effect on log (Yields)	Effect on log (Production workload)	Grown in tunnels	Grown outdoors
Cucumber	Fruit crop	0.63	3.06	1.15	1.22	Yes	Yes
Eggplant	Fruit crop	0.70	3.9	0.63	0.38	Yes	No
Endive	Raw greens	1.00	5.76	-0.85	0.02	No	Yes
Fennel	Cooked greens	0.57	3.72	-0.24	-0.24	Yes	Yes
French bean	Fruit crop	0.77	6.93	-0.26	-0.01	Yes	Yes
Garlic (storage)	Seasoning	0.31	5.98	-0.69	-0.12	Yes	No
Garlic (spring)	Seasoning	0.12	9.18	-0.88	0.02	Yes	Yes
Herbs	Seasoning	0.15	5.06	-0.38	-0.17	Yes	Yes
Kale	Cooked greens	0.50	4	-0.79	-0.19	Yes	Yes
Kohlrabi	Cooked greens	0.65	3.52	0.47	-0.27	Yes	Yes
Lamb lettuce	Raw greens	0.23	11.82	-0.86	0.29	Yes	Yes
Leek	Cooked greens	0.88	2.88	0.03	0.30	Yes	Yes
Lettuce	Raw greens	0.43	3.16	0.10	-0.42	Yes	Yes
Melon	Fruit crop	0.90	3.51	0.50	-0.12	Yes	No
Mixed salad leaves	Raw greens	0.22	11.29	-0.92	0.12	Yes	Yes
Onion (spring)	Seasoning	0.53	3.69	-0.22	0.06	Yes	Yes
Onion (storage)	Seasoning	0.63	3.07	0.10	0.17	No	Yes
Parsnip	Root crop	0.83	3.15	0.45	0.13	No	Yes
Pea	Fruit crop	0.53	7.71	-0.72	0.11	Yes	Yes
Potato (storage)*	Potato	1.00	2.1	0.20	0.13	Yes	Yes
Potato (early)	Potato	1.11	3.53	0.05	0.07	No	Yes
Radish (fresh)	Root crop	0.34	4.92	-0.31	-0.28	Yes	Yes
Radish (storage)	Root crop	0.60	2.89	0.28	-0.45	Yes	Yes
Shallot (storage)	Seasoning	0.24	5.69	-0.42	0.04	Yes	Yes
Spinach	Cooked greens	0.65	4.71	-0.82	0.06	Yes	Yes
Squash	Fruit crop	1.05	2.59	0.38	-0.39	Yes	Yes
Strawberry	Fruit crop	0.38	10.53	-0.45	0.14	No	Yes
Sweede (storage)*	Root crop	0.75	2.6	0.46	-0.45	No	Yes
Sweet pepper	Fruit crop	0.41	4.54	0.43	0.17	Yes	Yes
Tomato (cherry)	Fruit crop	0.28	6.58	1.05	1.26	Yes	No
Tomato (classic)	Fruit crop	1.33	3.12	1.66	1.27	Yes	No
Tomato (heritage)	Fruit crop	1.25	3.9	1.07	1.27	Yes	No
Turnip (fresh)	Root crop	0.63	3.18	0.23	-0.29	Yes	Yes
Turnip (storage)*	Root crop	0.75	2.64	0.46	-0.45	No	Yes
Zucchini	Fruit crop	1.20	2.55	0.86	-0.10	Yes	Yes

256 Storage, crops that can be stored.

257 * Indicates winter storage crops that are not grown in the 9-months marketing strategy selling from April to
258 December, described later.

259 Crop categories are families of crops expected by consumers in their boxes. Tomatoes, carrots, and potatoes were
260 so strongly expected that they were a category as such. These categories were used by the crop-planning sub-
261 model (SM3).

262 A “crop share” is the quantity of crop required for one vegetable box (mean of 10 microfarms used in SM3 and
263 to calibrate the model).

264 Effect on log (Yields) and log (Production workload) are predictions used in SM1 and SM2, respectively, in log
265 ($\text{kg}\cdot\text{m}^{-2}$) and log ($\text{min}\cdot\text{m}^{-2}$).
266
267

268 **2.4. Predicting yields and production workload**

269 *2.4.1. Developing linear mixed models*

270 We aimed to assess the effects of the four farming practice variables on yields and on
271 production workload, independent of the particular farm or crop. We used linear mixed models
272 that held the four farming practices as fixed effects and considered the farm and crop as
273 independent random effects. The rationale behind the use of mixed models was to account for
274 the correlation between measures on the same farm or for the same crop which were considered
275 as nested. Moreover, considering farms and crops as random effects allowed us to predict the
276 impact of each level of crops and farms despite the limited number of observations thanks to an
277 effect of “shrinkage” incorporated in the mixed model approach that lowered extreme
278 estimations. Extreme estimations could occur due do the sampling design where only one
279 measure was performed for each crop in each farm. Hence the mixed model approach was here
280 a method of choice.

281 Mixed models were built based on 387 observations of yields (Y) [$2.86 \pm 2.35 \text{ kg}\cdot\text{m}^{-2}$ (SD
282 throughout), range 0.18–13.9] and production workload (Wp) ($39.6 \pm 36.7 \text{ min}\cdot\text{m}^{-2}$, range
283 5–23.1) for the combinations of the 10 farms and 50 crops. Depending on farms, data were
284 collected about 30 to 48 crops. Depending on crops, data were collected on 4 to 10 farms. To
285 obtain the required homoscedasticity of residuals, the two response variables were transformed
286 with decimal logarithm to log(Y) and log(Wp). A backward selection of variables ($*p<0.05$)
287 led to two final parsimonious sub-models (SM). These two sub-models were SM1 (**Table 3**)
288 for log(Y) and SM2 for log(Wp) (**Table 4**). These models were generated using lme4 in R
289 version 3.3.1 (Bates, 2010). The goodness of fit was assessed with a conditional R-squared that
290 describes the proportion of variance explained by both the random and the fixed factors.

291

292

Table 3

293

Sub-model 1 (SM1), a linear mixed model for log(Y) [yield in log (kg·m⁻²)].

294

Fixed effects

	Estimated	Std error	<i>p</i> ***
Intercept*	0.38	0.13	
Mechanization only for tillage**	0.48	0.12	<0.0001
Manual labor only**	0.32	0.13	0.01

*Mechanization for most farming activities. **Discrepancy from intercept. ****t*-test.**Random effects**

	Variance
Crop	$\hat{\sigma}_C^2 = 0.49$
Farm	$\hat{\sigma}_F^2 = 0.018$
Residual	$\hat{\sigma}_e^2 = 0.18$

Goodness of fit: Conditional R² = 0.75.

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Table 4

306

Sub-model 2 (SM2), a linear mixed model for log(Wp) [production workload in log (min·m⁻²)].

307

Fixed effects

	Estimated	Std error	<i>p</i> ***
Intercept*	3.08	0.15	
Presence of low-input practices**	0.47	0.21	0.03
Self-built equipment**	0.51	0.18	0.004
Mechanization only for tillage**	-0.37	0.19	0.06
Manual labor only**	-0.12	0.23	0.06

*Mechanization for most farming activities, absence of low-input strategies, and absence of self-built equipment. **Discrepancy from intercept. ****t*-test.

Random effects

	Variance
Crop	$\hat{\sigma}_C^2 = 0.42$
Farm	$\hat{\sigma}_F^2 = 0.042$
Residual	$\hat{\sigma}_e^2 = 0.13$

Goodness of fit: Conditional $R^2 = 0.76$.

308

309 The only significant fixed effect on yields was the level of mechanization. This value was
 310 significantly higher for “manual labor only” and “mechanization only for tillage” because they
 311 allowed higher planting density. These schemes did not implement mechanized weeding, which
 312 required more space between the crop rows.

313 The significant fixed effects on production workload were the level of mechanization, the
 314 presence of low-input practices, and self-built equipment. “Manual labor only” and
 315 “mechanization only for tillage” led to lower workload compared with mechanization for most
 316 cropping practices. Higher cropping densities reduced the workload dedicated to weeding,
 317 because weeds had less space to invade crops (Liebman and Davis, 2000). Farmers who used a
 318 tiller only for tillage or manual labor also tended to till the soil less frequently than farmers with
 319 a tractor. The use of mechanization for tillage at the same high density of planting reduced
 320 workload. Low-input practices and self-built equipment resulted in a higher workload. The
 321 predicted effects for the 50 crops on $\log(Y)$ for yields and $\log(Wp)$ for production workload are
 322 presented in **Table 2**. Intercropping did not significantly affect yields or workload. The impact
 323 of climate also was also tested, but it was not significant.

324 2.4.2. *Building three coherent technical systems*

325 Farming practices were combined to build three coherent technical systems. For each
326 technical system, yields and production workload estimates were based on sub-model 1 and
327 sub-model 2 and considered the specific modality of level of mechanization, low-input
328 practices, and intercropping. The self-built equipment variable was used to characterize the
329 effect of investment strategies, which are described below. The three organic technical systems
330 are (1) manual microagriculture, (2) bio-intensive market gardening and (3) classic diversified
331 market gardening.

332 The manual system was designed to produce a large quantity of food on a small amount of land.
333 The land-use objective was high, and included 2 to 6 cropping cycles per plot per year. This
334 intense schedule relied on intercropping and excluded green manure, but implement other low-
335 input practices. The bio-intensive system maximized productivity per unit area by conducting
336 high-density planting. Mechanization was used for superficial tillage. Intercropping was not
337 practiced because it was perceived as a source of complexity in crop management. Low-input
338 practices were implemented. The maximum number of crops were grown in one plot each year,
339 but green manure was integrated into the rotation, which reduced the land-use objective
340 compared with the manual system. The bio-intensive system had from 1 to 4 cropping cycles
341 per year. The classic system was inspired by current farming practices that are common in
342 diversified organic market gardening in France. In classic systems, mechanization was used for
343 most cropping activities, no intercropping or low-input practices were implemented, it was not
344 designed to optimize land use, and there were only one or two cropping cycles per plot per year.

345

346 **2.5. Modeling crop planning to match commercial requirements**

347 2.5.1. *Considering two marketing strategies*

348 Most microfarms in this study sold family-sized vegetable boxes on a weekly basis, usually
349 with a one-season contract within the framework of CSA. The marketing season for these farms

350 ranged from 9 to 12 months. Two contrasting strategies for marketing the vegetables boxes
351 were considered in the model by varying the marketing season length and the crops sold: (1) A
352 marketing period of 12 months modeled farmers selling a wide range of crops throughout the
353 year, including winter storage crops. Only the first two weeks of January were reserved for
354 holidays; (2) A marketing period of 9 months from April to December modeled farmers
355 reserving some of the winter for holidays. Winter storage crops were not grown (**Table 2**).

356 2.5.2. *Generating random cropping plans based on marketing with sub-model 3 (SM3)*

357 Sub-model 3 (SM3) was a combination program developed with R version 3.3.1, that
358 generated random cropping plans providing convenient diversity and quantity of crops for one
359 family-size vegetables box throughout the marketing season, which is crucial for consumers
360 loyalty (Navarrete et al., 2009). Based on a collective workshop with 3 farmers (whose results
361 were validated by all farmers), crop planning criteria were modelled the following way:

- 362 • Vegetables boxes had to present every week a balance between eight categories of
363 crops: (**Appendix A**). Tomatoes, carrots and potatoes were considered as a single
364 standing category because of their importance in consumers' preferences.
- 365 • Quantity and diversity criteria were characterised for every month and each category of
366 crop considering that 4 different vegetables boxes were sold every month. The expected
367 quantities of crops in a weekly family-sized vegetable box varied according to the crop,
368 and were designated as 'crops shares' (**Table 2**). Quantity criteria were expressed in
369 number of shares per month and diversity criteria in number of different crops present
370 in the boxes over the month (**Appendix A**). For the 12-months marketing strategy, 2
371 weeks of holidays were considered in January which decreased the number of shares
372 required this month.

- 373 • A trimester diversity criteria was integrated to guarantee the diversity not only during
374 the month but also throughout the year which was a key point in consumer loyalty. To
375 guarantee the year-round diversity, at least 30 crops had to be marketed.
- 376 • As the diversity and quantity of crops required depended on the marketing strategy,
377 criteria were characterised for 9-months and 12-months marketing strategies.
- 378 • As the diversity and quantity of crops available depended on the climate, criteria were
379 characterised for the cool and the mild climate considered in the study (**Appendix A**).

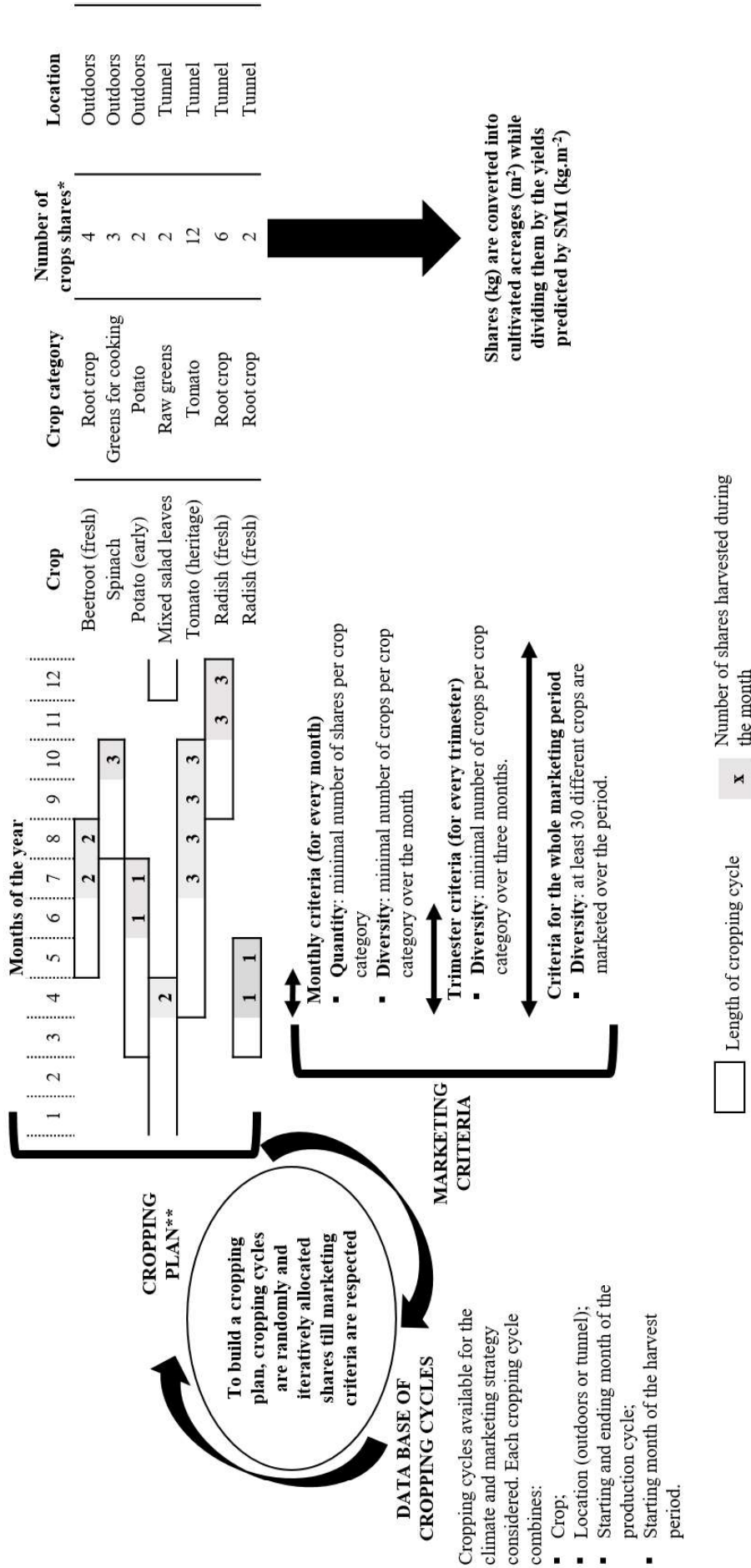
380 For each crop, the minimal number of crops shares per harvesting month (SHmin) was
381 characterised. This minimal number of shares was based on the consideration that some crops
382 had to be harvested various times a month and had therefore to be included various times in the
383 vegetables boxes of the month. SHmin was 2 for eggplant, French beans, sweet peppers and
384 tomatoes, 4 for courgettes and cucumbers and 1 for all other crops. For all crops the maximal
385 number of crops shares per harvesting month (SHmax) was 4. SM3 selected iteratively month
386 after month from the cropping cycles database the cropping cycles allowing a harvest during
387 the month. Each time, a crop and a cropping cycle were randomly chosen among these
388 possibilities and a number of shares was affected to it. If this cropping cycle had not been
389 affected shares before, the number of shares affected was SHmin multiplied by the length of
390 the harvest period (in months). If this cropping cycle had been affected shares before and its
391 number of shares was less than SHmax multiplied by the length of the harvest period, the
392 number of additional shares affected to the cropping cycle was 1. At the end of each iteration,
393 the average number of shares harvested per crop and per month was calculated considering that
394 all shares of a cropping cycle were allocated homogeneously over the harvest period. The
395 number of different crops per month was also calculated. As long as diversity and quantity
396 criteria (**Appendix A**) were not respected for the month, another iteration started for the same
397 month. If conditions were respected, SM3 stepped to the next month. At the end of the process,

398 trimester diversity criteria were checked. If they were not respected, the process started again
399 from the beginning. This iterative process was run separately for each of the 8 categories of
400 crops. Then, cropping cycles of the 8 categories of crops and their respective number of shares
401 were aggregated. A final yearly diversity check controlled that at least 30 crops were marketed
402 over the year.

403 To extend the harvest period of a crop, microfarmers combined cropping cycles with
404 overlapping harvest periods. For example, to harvest French beans from July to September,
405 market gardeners could combine a cropping cycle of French beans planted in March and
406 harvested from July to August and a cropping cycle implanted in April and harvested from
407 August to September. However, the fact that the harvests of these two cycles overlapped in
408 August did not mean that customers received twice as many shares of French beans in August
409 but that the shares of French beans in August came from both cropping cycles. The possibility
410 of combining cropping cycles was integrated in SM3. Each time that a cropping cycle was
411 randomly selected by the model, it was combined to the cropping cycles of the same crop with
412 overlapping harvest period which had been affected shares before (if existing) to create an
413 extended cropping cycle which was managed by the model exactly as a regular cropping cycle
414 whose length was the extended harvest period. This way, the minimal and maximal number of
415 shares per month applied for the combination and not for the individual cropping cycles
416 composing it. Such combinations were not limited in the number of cropping cycles they could
417 integrate.

418 The total number of crops shares affected at every cropping cycle was converted into
419 cultivated acreage based on the yields predicted by SM1 (depending on farming practices) and
420 the mean weight of shares (**Table 2**) as explained in **Fig. 4**. This resulted in a cropping plan
421 characterized by a cultivated acreage affected to different cropping cycles running over the

422 year. In terms of spatial allocation, the only explicit criteria considered in this cropping plan
423 was the location in the tunnel area or in the outside field attached to each cropping cycle.



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Fig. 4. Illustration of the crop-planning sub-model (SM3) for a 9-month marketing strategy in the cool climate. * A “crop share” is the quantity of crop required for one vegetable box, which varies between crops as indicated in **Table 2**. **Cropping plan refers to the cultivated acreage attached to all selected cropping cycles. Cultivated acreage is calculated based on the crops shares required to match marketing criteria. Here, only a few cropping cycles are presented for illustration, but many more would be required to match the marketing criteria. Cropping plans were designed to provide one weekly vegetable box (four boxes per month) during the marketing period.

429 2.5.3. *Conversion of cultivated acreage to utilized agricultural area*

430 The cultivated acreage of all cropping cycles present each month were summed for the
 431 tunnels and the outdoor area. The utilized agricultural area (UAA) was calculated for the
 432 outdoor and tunnel areas by dividing the highest monthly cultivated acreage by a parameter
 433 called the maximal cropping intensity (MCI), which accounted for the land-use objective of
 434 each technical system and integrated the practices of intercropping, growing green manure, and
 435 leaving land fallow between cropping cycles. Higher MCI values denote more intensive land
 436 use. The range of MCI values for each technical system and location is presented in **Table 5**.
 437 For each simulation, a MCI value in tunnel and outdoor areas was randomly drawn from their
 438 respective range of values.

439 **Table 5**

440 Range of maximal cropping intensity (MCI) for different technical systems according to land-use objective.

441

Location	MCI	Technical system		
		Manual	Bio-intensive	Classic
Tunnel	Min	1.6	1	1
	Max	2	1	1
Outdoor field	Min	1	0.6	0.4
	Max	1.4	1	0.8

442

443 The acreage of footpaths between cropping beds was integrated by considering that footpaths
 444 represented 20% of UAA in tunnels and 35% of UAA outdoors according to farm observations.
 445 The global share of tunnels in UAA was calculated.

446 **2.6. Simulating incomes and utilized agricultural area for a full-time farmer**

447 *2.6.1. Considering three investment hypotheses for costs and subsidies*

448 Our model considered that farmers had no initial capital and had to acquire 5-year bank
 449 loans to cover the initial investment. Three investment hypotheses were considered in the
 450 simulations: (1) In a low-cost setup, the farmer built his equipment (self-built) using second-
 451 hand material. This strategy reduced investment costs but increased the production workload;
 452 (2) In a high-cost setup, the farmer bought all new equipment. This strategy reduced workload

453 but increased investment costs; (3) In the running phase, investment bank loans had been paid
454 off (five years after initial startup).

455 Costs and subsidies are described in **Table 6** and **Table 7** for a microfarm managed by a
456 single farmer. It was assumed that the land was bought and included a basic acreage of 3,000
457 m² for a building and an access road (not included in UAA but bringing costs).

458 **Table 6**

459 Annual global costs, expenses, and subsidies (in EUR) for the three technical systems.

Technical system		Manual	Bio-intensive	Classic
Variable costs	Seeds and plants, fertilizers and phytosanitary products, other production supplies, and small equipment	11% of sales	11% of sales	20% of sales
Fixed costs per farm	Water, electricity, fuel, equipment maintenance, and other expenses (administrative tasks, organic certification)	5,000	6,500	8,000
	Social security and insurance		4,000 in all cases	
	Subsidy per farm*	2,755 in all cases		
	Subsidy per m ² *	0.085 in all cases		

461 * Includes specific subsidies for organic farming and general agricultural subsidies in France per farm and
462 per unit area of UAA.

466 **Table 7**

467 Additional costs and subsidies (in EUR) during the setup period.

Technical system	Manual		Bio-intensive		Classic	
	Low-cost setup	High cost setup	Low-cost setup	High cost setup	Low-cost setup	High cost setup
Initial fixed investment per farm*	15,000	25,000	25,000	35,000	35,000	45,000
Investment cost per m ² of tunnels with irrigation	10	30	10	30	10	30
Investment cost per m ² to buy the utilized agricultural area	0.5 in all cases					
Annual bank loans to pay	Initial investment divided by 5 years + annual interest calculated with an interest rate of 3%.					
Annual setup subsidy per farm	3,000 in all cases					

468 Investment for 3,000 m² of land, water drilling, mechanized and manual tools, low-cost delivery van, and small
469 storage building.

470
471

472 *2.6.1. Calculating incomes and utilized agricultural area according to annual workload*

473 Based on the cropping plan and mean crop prices (**Table 2**), the global sales value attached
474 to the production of one vegetable box throughout the marketing season was calculated. The
475 workload required to generating these sales value was quantified based on the production
476 workload attached to the different crops predicted by SM2, and considering that administrative
477 and commercial tasks represented 20% of annual workload. The UAA required for this
478 production had been calculated as above-mentioned based on SM3.

479 To calculate the global sales and the UAA on the farm, we assumed that the global
480 production of the farm was a linear combination of identical vegetable boxes with similar
481 cropping plans. The number of vegetable boxes produced depended on the global annual
482 workload considered for a single farmer. To calculate incomes, costs and subsidies described
483 in **Table 6** and **Table 7** were respectively deducted or added to sales, considering the previously
484 determined share of tunnels in UAA (**Fig. 1**).

485 **2.7. An application of MERLIN to validate the model**

486 *2.7.1. Integrating stochasticity in simulations*

487 To validate the model, we ran simulations for the different climates and contrasted strategic
488 options that were designed with farmers. We considered 3 possible level of annual workload
489 as input variable to cover the diversity observed on the field (1,800h; 2,500h and 3,000h). For
490 each combination of technical system (3 possible), marketing strategy (2 possible), investment
491 hypothesis (3 possible), climate (2 possible), and level of annual workload (3 possible), we ran
492 1000 simulations leading to 108,000 ($3*3*2*2*3*1000$) simulations. The simulation process is
493 detailed in **Fig. 1**. A total of 1,000 simulations was implemented for each combination of input
494 variables because the average and median incomes and UAA stabilized after 600 to 850
495 simulations depending on combinations of input variables. Simulations were not ran to
496 maximize incomes but to the explore the variability of incomes possible over one production

497 year due to the variability of yields, workload and cropping plan observed on the field and
498 modelled with SM1, SM2 and SM3. For each simulation, fixed effects of SM1 and SM2 were
499 drawn in the normal distribution of the parameter estimates. Random farm effects and residual
500 effects on yields (Y) and production workload (Wp) were drawn from their normal distributions
501 to integrate farm variability (see **Table 3** and **Table 4**, respectively). Fixed effects, farm effects,
502 and residual effects were added to the predicted effect for each crop (**Table 2**) to predict yield
503 (Y) and production workload (Wp) according to the selected technical system and investment
504 hypothesis. A cropping plan was randomly generated by SM3 for each simulation.

505 Our model was stochastic because a given combination of input variables (set of strategic
506 choices, climate, annual workload) led to variable incomes and UAA. We integrated
507 stochasticity to account for the uncertainty that was inherent in the model due to the small
508 number of farms in the sample, and to explore a wide range of possible situations.

509 *2.7.2. Validating the model*

510 Modeling outputs are generally validated by comparing fitted values to real values from a
511 large independent data set (Bellochi et al., 2010). Given the fact that microfarms are really
512 innovative and new systems in France, it was impossible to access such large data set. We only
513 managed to obtain data for 12 microfarms not belonging to our sample. We also compared
514 the simulations with the 10 farms from the initial sample to ensure that our modeling hypotheses
515 at different levels of MERLIN accurately represented the initial case studies. MERLIN was a
516 stochastic model that provided a range of values for one set of input variables. Therefore, we
517 considered that visual validation was sufficient to ensure that the real values were contained
518 within this range. A sensitivity analysis was implemented for the major parameters of this
519 model (**Appendix B**).

520 The type of validation for models depends on the objective for which the model was
521 developed (Bellochi et al., 2010). In our case, the central objective was to provide insights about

522 the effects of different strategies on microfarm incomes and UAA. These simulations and
523 results were targeted for use by microfarmers and public organizations. In agreement with our
524 grounded modeling approach, we considered that the central validation of MERLIN had to
525 come from practitioners (Troitzsch, 2004). MERLIN was presented in ten 2-hours collective
526 workshops with more than 300 practitioners including microfarmers, organic market gardening
527 advisors, and teachers. In each workshop, the architecture and parameters of MERLIN were
528 detailed (e.g. impacts of the different practices on yields, costs, prices, crop planning criteria...)
529 during one hour and modelling outputs were presented during 30 minutes, the last 30 minutes
530 were dedicated to exchanges with practitioners. We used the validation criteria defined by Cash
531 et al. (2003): credibility (scientific adequacy), saliency (relevance to decision makers), and
532 legitimacy (fair and unbiased information that respected stakeholders' values and beliefs). To
533 launch the discussions, we asked the questions: (i) do you think the results are credible? ; (ii)
534 are the modelling outputs useful and why ? ; (iii) what would you have expected from the
535 model that is missing ? ; (iv) do you trust the results? : (v) what do you think of this research
536 project ?. Answers and exchanges stimulated by these questions were analyzed with the same
537 qualitative method used for semi-structured interviews focusing on the validation.

538 *2.7.3. Statistical analysis of modelling outputs*

539 Incomes were expressed as incomes per hour labor to compare the performances of farms
540 with different levels of annual workload. Pairwise comparisons of mean levels of income per
541 hour and UAA were performed with t-test (5%) with unequal variances across simulations.

542 **3. Results**

543 *3.1.1. Comparison of predicted outputs with data from actual microfarms*

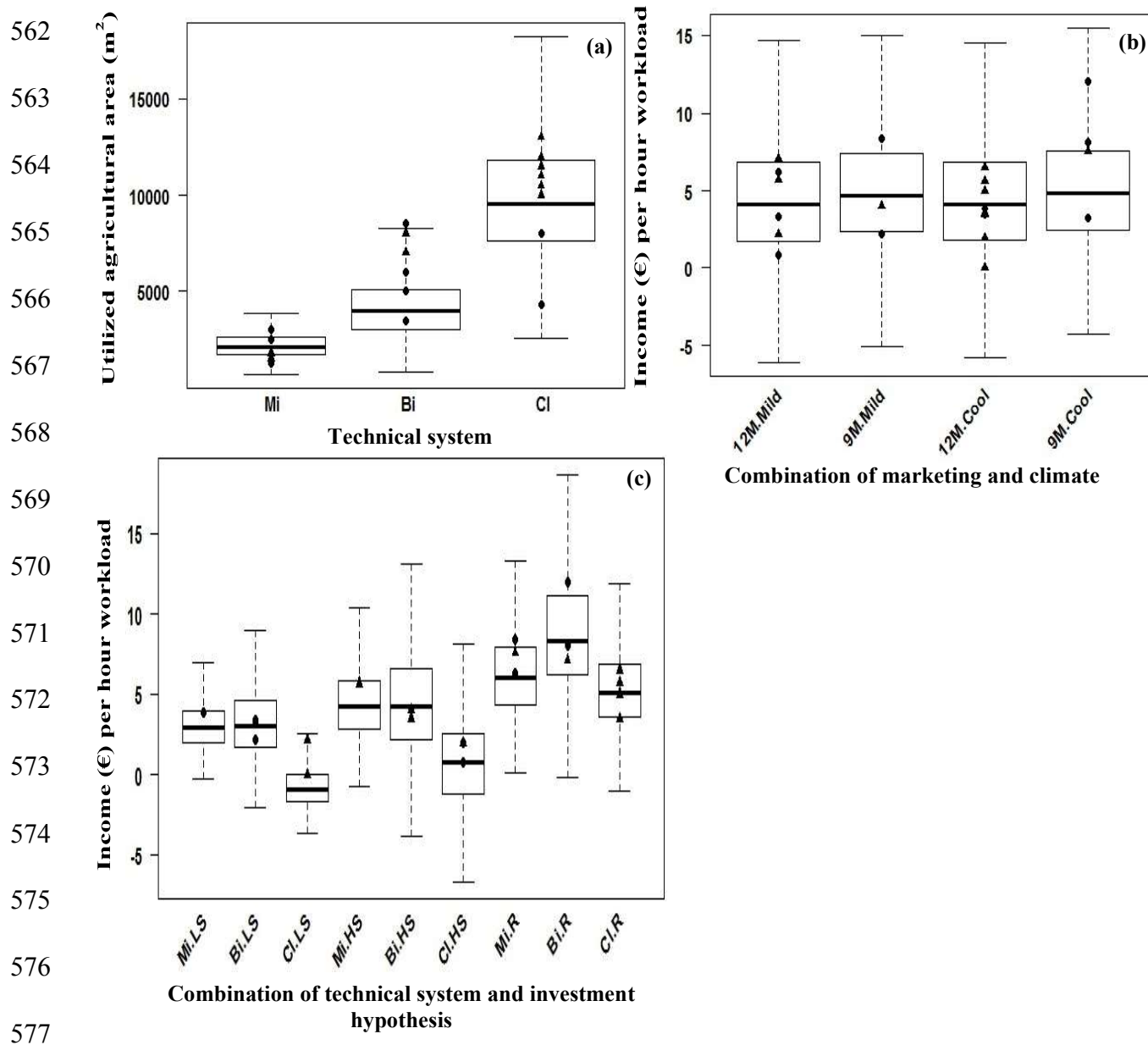
544 Comparisons of a sample of simulated outputs and real farm data showed that real farm data
545 were within the same range as the values predicted by MERLIN (**Fig.5**). The model accounted
546 for the large variability that existed between farms. The relative variations of values depending

547 on the input variables (patterns) were well represented by the model (Küppers and Lenhard,
548 2005).

549 The UAA was the smallest in the manual system and the highest in the classic system,
550 which was consistent with the relative land use objective of each system: high in the manual
551 system, lower in the classic system and intermediary in the bio-intensive system (**Fig.5a**).

552 In the running phase, the bio-intensive technical system generated the highest income per
553 hour workload, followed by the manual system and the classic system. In both setup phases
554 (low or high-cost), the manual and bio-intensive systems with less initial investment generated
555 more income than the classic system whose investment was increased by a high level of
556 mechanization. The high-cost setup led to higher levels of incomes than the low-cost setup
557 because the workload the decrease of investment costs allowed by the low-cost strategy did not
558 mitigate the increase of workload due to self-building of equipment (**Fig.5c**).

559 The 9-month marketing strategy led to higher income than the 12-month strategy because
560 it did not produce winter storage crops, which had lower added value compared with other
561 crops. Climate had no significant impact (5%) on incomes (**Fig.5b**).



578 **Fig. 5.** Comparisons of modeling outputs and real data for (a) utilized agricultural area according to the technical
579 system, (b) income per hour workload according to marketing and climatic conditions, and (c) income per hour
580 workload according to the technical system and investment hypothesis. Boxplots are generated by the model.
581 Circles represent average data from the sample (10 data points); triangles represent average data from other farms
582 (12 data points).

583 Technical systems: Mi, manual microagriculture; Bi, bio-intensive; Cl, classic.

584 Marketing strategies: 12M, 12-months marketing strategy including winter storage crops; 9M, 9-months marketing
585 strategy excluding winter storage crops.

586 Investment hypotheses: LS, low-cost setup; HS, high-cost setup; R, running phase.

587

588

589 3.1.2. Practitioner validation of the model

590 The MERLIN model was deemed to be credible by practitioners, based on their

591 observations that its estimated outputs were consistent with the traits and diversity of real farms.

592 The predicted order of magnitude of the income per hour labor and UAA (**Fig. 5**) were in
593 agreement with practitioners' expectations. However, the extreme values of the boxplots were
594 either overestimates or underestimates (as discussed later). The practitioners considered the
595 model to be salient, as the main issues and questions concerning microfarms were addressed,
596 especially those pertaining to future farmers who wondered whether it was realistic or not to
597 start a microfarm without a tractor and in which extent excluding winter storage crops from
598 marketing or self-building of equipment could improve incomes. The required utilized
599 agricultural area according to strategies was also really expected by future microfarmers as
600 agricultural organizations often advise them to buy more land that they are able or willing to
601 given their limited capital. However, farmers mentioned that they would be interested in
602 investigating in which extent some crop planning configurations would impact income given a
603 set of strategic options, climate and annual workload. So far, we have not analyzed modelling
604 outputs in the light of crop planning configurations but farmers claimed that such type of
605 information would be really useful as a decision support. Further analysis will therefore be
606 carried out in this direction.

607 The model was perceived as legitimate because it was based on farm data that were mostly
608 collected by farmers, designed thanks to farmers' expertise, and participation. Farmers argued
609 that the legitimacy of our approach also relied on the fact that our approach was not perceived
610 as prescriptive because we did not seek to determine an optimal set of strategies but explored
611 contrasted options that decision makers were free to evaluate themselves depending on their
612 objective.

613 **4. Discussion**

614 *4.1. Economic performance of microfarms*

615 The model application showed that microfarms implementing low-input practices with
616 intense land use (high planting density, more crop successions per plot per year, and
617 intercropping) could potentially generate higher income with less land than microfarms
618 applying classical strategies for organic market gardening. These results are in agreement with
619 some previous studies showing that small farms can be more productive and efficient than
620 bigger farms (Carter, 1984; Rosset, 2000).

621 Our model results indicate that marketing and investment strategies have key roles in
622 microfarm income, whereas most available information focuses on technical aspects. Future
623 work will explore in greater depth the economic viability of microfarms using the modeling
624 outputs of MERLIN.

625 *4.2. Limits of the model and perspectives*

627 The model had low sensitivity to the parameters related to yield (**Appendix B**). It was highly
628 sensitive to SM2 parameters predicting production workload, price levels, fixed costs, initial
629 investments for tunnels, and setting up subsidies. Further model development will require to
630 carry out more precise measurements of these parameters. Variations of the sensible parameters
631 may be the basis of other scenarios for investigation (e.g., comparing high-selling price and
632 low-selling price scenarios).

633 The major limit of our model was the limited sample used (10 farms) and the limited
634 independent dataset to validate quantitatively the simulation outputs (12 farms). This difficulty
635 is intrinsically connected to the fact that microfarms are new and innovative farming systems.
636 We developed the MERLIN model to answer the pressing question of microfarms incomes
637 although we were aware of the limited access to data to carry out this study. Our grounded

638 modelling approach, based on farmer's expertise and participation was a pragmatic solution to
639 overcome this difficulty. We considered that given the lack of data about microfarms, validation
640 by practitioners (more than 300) was the most reliable solution at this stage. However, this
641 advocates for prudence and reserve about the results of our study. The number of microfarms
642 is quickly growing in France and further research should definitely aim to enlarge datasets to
643 calibrate and validate the model, strengthen or mitigate our results.

644 The extreme values predicted by the model resulted from the stochastic logic of randomly
645 drawing fixed-parameter estimates of SM1 and SM2, to account for the uncertainty linked to
646 the limited sample. Collecting more data would allow us to consider the mean parameter
647 estimates and reduce the extreme values of income and UAA that stakeholders judged
648 unrealistic.

649 The data collected to build SM1 and SM2 were mean yields and workload for each crop
650 considering the annual production, workload and cultivated acreages on the farm including
651 tunnels and outdoors area. These mean yields and workload were affected similarly to all
652 possible cropping cycles of a given crop without accounting for possible variability within the
653 year and according to its location (in tunnels or outdoors). This may lead to underestimations
654 of yields in tunnels and overestimations of outdoors yields for crops which are grown both
655 outdoors and in tunnels. Same way, some crops may be more productive in summer than in
656 winter and for a given crop workload may vary depending on the time of the year. Most crops
657 are sold quickly after harvesting but for winter storage crops, storage losses (and therefore
658 marketable yields) may vary depending on the harvest time. As the crop planning sub-model
659 imposes a diversity of crops over the year to match direct-selling marketing requirements, it
660 generates cropping plans where a given crop tends to be grown at different times of the year
661 and in different locations. At the scale of the production year, workload and incomes
662 estimations are therefore expected to be consistent with the mean values considered. However,

663 more precise measurements would be required to correct possible biases if incomes and
 664 workload are to be studied at the scale of the month, which is a major challenge in market
 665 gardening where temporary peaks workload can bring real difficulties for farmers.

666 Other limitations of MERLIN are listed in **Table 8**, along with further investigative
 667 strategies that should strengthen its salience.

668 **Table 8.**

669 Limits of the MERLIN model and further investigation perspectives.

Limit	Perspective
Estimations of workload per crop relied on farmers' judgement and are sensitive parameters.	Carry out workload measurements on a wider sample of farms.
Most microfarms used to calibrate the data, whether implementing low-input practices or not, used plastic mulch to reduce weeding for certain crops (embodied in the workload, yields and costs data). The frequency of plastic mulch use varied between farms and crops.	Collect more data to model the impact of the level of plastic mulch use on workload, yields, and costs.
In the studied area, climate only impacts cropping cycle possibilities but not yields.	Collect more data in contrasting climates to characterize the potential impact of climate on yields
We assumed that crop diversity resulting from marketing criteria always allowed effective intercropping based on the complementarity of rooting depths, plant heights, and maturing period.	Characterize each of the 50 crops with their rooting depths, heights, and maturation periods to integrate intercropping criteria in crop planning.
Crop planning only referred to two zones in terms of spatial allocation, outdoors or in tunnels, and did not account for soil specificity.	Further develop a spatially explicit model accounting for soil conditions and rotation criteria (Dogliotti et al., 2005).
Rotation criteria were not explicitly considered considering the postulate that direct-selling constraints guaranteed a balance between botanical families at the farm scale.	
Climatic and ecological uncertainties or accidents were not considered.	Integrate the possibility of extreme events in the model and discuss adaptation strategies with farmers in simulation-based participatory workshops (Martin et al., 2013).

670

671

672 **5. Conclusion: Grounded models for radical organic farming systems?**

673

674 Although expert knowledge has been widely used to design specific compartments of
675 simulation models that integrate biophysical and socioeconomic components of farming
676 systems (Rossing et al., 2007), the theoretical basis of simulation models has relied primarily
677 on the integration of academic knowledge from various disciplines (Oriade and Dillon, 1997;
678 Stoorvogel, 2004; Jansen and Van Ittersum, 2007). However, rich academic knowledge is not
679 always available for ROFS, which are often sparse individual initiatives.

680 Agroecological studies have highlighted the importance of farmer-based innovations for the
681 development of more sustainable food systems (Holt-Giménez and Altieri, 2013). Martin et al.
682 (2013) proposed that simulation models are a valid way to support exploratory innovations if
683 farmers are involved at various steps of the modeling process. In this grounded modeling
684 approach, practitioners were involved in defining the problem to be solved, bringing knowledge
685 and expertise to build the model, and validating it in a pragmatic, interactive, and inductive
686 perspective. This collaboration led to an original model, MERLIN, which addressed the key
687 challenge of crop planning for diversified farms that sell through short supply chains. The
688 challenge of building this kind of model has been qualitatively described (Navarrete, 2009), but
689 to our knowledge, never simulated.

690 The model enabled exploration of innovative technical systems based on farm data, and
691 examination of low-cost investment strategies that are often encouraged in alternative farmers'
692 networks. When we validated the model with practitioners, we did not ask specific question
693 about the added value of our modelling approach compared to optimization models.
694 Nevertheless, practitioners said spontaneously that they appreciated that we “gave every
695 scenario a chance” and did not seek to identify an optimal set of strategies, which is typical for
696 simulation models relying on linear programming (Rossing et al., 2007). This aspect was central
697 in the legitimacy of our model because radical organic farmers are often reluctant to use top-
698 down and prescriptive approaches. The results of this study, highlighting that low-input

699 practices with intensive land use generate higher income on less land, may have been reached
700 with an optimization approach and could be considered as prescriptive. However, farmers told
701 us that they would prefer sub-optimal set of strategies for other reasons than economic
702 objectives. For example, for some farmers the manual technical system is not an option because
703 they consider that manual labor increases work hardness whereas for other manual labor is
704 preferable to mechanization because they want to “get their hands in the dirt”. Investigating and
705 presenting all sets of strategies designed by farmers without aiming to determine an optimal
706 one provides a richer material for further discussions where farmers are free to react and
707 comment the modelling outputs based on other rationalities than just maximizing incomes.
708 Deeper discussions with farmers on a wider sample of modelling outputs, involving other
709 modalities for input variables may open original perspectives for research that may not have
710 come to light while only focusing on the optimal option. Such workshops were developed based
711 on the MERLIN model in and will be presented in a future paper.

712 In conclusion, we consider that grounded modeling is a promising way to explore innovative
713 ROFS. However, the epistemological and methodological implications of grounded modeling
714 require further investigation. This may benefit from a wider framework of transdisciplinary
715 strategies developed in agroecological studies, which integrate the knowledge of stakeholders
716 and academics using problem-solving approaches (Méndez et al., 2013).

717 **Acknowledgements**

718 We thank all farmers who dedicated time and energy to this research project. We also thank
719 the Ile-de-France Region for financial support for this work through DIM ASTREA; Agnes
720 Bellec-Gauche for her accountancy skills; and Rodolphe Sabatier and Guillaume Martin for
721 their constructive feedback and support.

722

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Appendix A. Marketing criteria for vegetable boxes according to climate and marketing strategy (year from January = 1 to December = 12).

Crop category	Climate	Marketing strategy	Min. nb. of crops shares per month												Min. nb. of crops per month												Min. nb. of crops per trimester			
			1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
Carrot	Mild	9M	0	0	0	2	2	2	2	2	2	2	0	0	0	0	1	1	1	1	1	1	0	0	0	1	1	1	1	
Carrot	Cool	9M	0	0	0	2	2	2	2	2	2	0	0	0	0	0	1	1	1	1	1	1	0	0	0	1	1	1	1	
Seasoning	Mild	9M	0	0	0	4	4	4	4	4	4	4	0	4	0	0	2	2	2	2	2	2	1	1	0	3	2	3	3	
Seasoning	Cool	9M	0	0	0	4	4	4	4	4	4	4	0	4	0	0	2	2	2	2	2	2	1	1	0	3	3	3	3	
Fruit crop	Mild	9M	0	0	0	3	3	8	8	8	8	3	3	0	0	0	2	4	4	4	4	3	1	1	0	3	5	4	4	
Fruit crop	Cool	9M	0	0	0	2	2	8	8	8	8	3	3	0	0	0	1	2	4	4	4	3	1	1	0	3	5	4	4	
Potato	Mild	9M	0	0	0	2	2	2	2	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0	
Potato	Cool	9M	0	0	0	2	2	2	2	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	1	1	0	0	
Root crop	Mild	9M	0	0	0	2	4	1	1	1	1	4	4	0	0	0	1	2	1	1	1	1	2	2	0	3	2	4	4	
Root crop	Cool	9M	0	0	0	2	4	1	1	1	1	4	4	0	0	0	1	2	1	1	1	1	2	2	0	3	2	4	4	
Tomato	Mild	9M	0	0	0	0	4	4	4	4	4	0	0	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1	
Tomato	Cool	9M	0	0	0	0	4	4	4	4	4	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	
Raw greens	Mild	9M	0	0	0	4	4	4	4	4	4	4	4	0	0	0	1	1	1	1	1	1	1	1	0	2	2	2	2	
Raw greens	Cool	9M	0	0	0	4	4	4	4	4	4	4	4	0	0	0	1	1	1	1	1	1	1	1	0	2	2	2	2	
Cooked greens	Mild	9M	0	0	0	4	4	1	1	1	1	4	4	4	4	0	2	2	2	2	2	2	2	2	0	4	4	4	4	
Cooked greens	Cool	9M	0	0	0	4	4	1	1	1	1	4	4	4	4	0	2	2	2	2	2	2	2	2	0	4	4	4	4	
Carrot	Mild	12M	2	4	4	2	2	2	2	2	2	2	2	4	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Carrot	Cool	12M	2	4	4	2	2	2	2	2	2	2	2	4	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Seasoning	Mild	12M	2	4	4	4	4	4	4	4	4	4	4	4	4	2	2	2	2	2	2	2	2	2	3	3	3	3	3	
Seasoning	Cool	12M	2	4	4	4	4	4	4	4	4	4	4	4	4	2	2	2	2	2	2	2	2	2	3	3	3	3	3	
Fruit crop	Mild	12M	2	2	2	3	8	8	8	8	8	3	3	1	1	1	2	4	4	4	3	1	1	1	1	3	5	4	4	
Fruit crop	Cool	12M	2	2	2	2	2	8	8	8	8	3	3	1	1	1	2	4	4	4	3	1	1	1	1	3	5	4	4	
Potato	Mild	12M	2	4	4	2	2	2	2	2	2	2	2	4	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Potato	Cool	12M	2	4	4	2	2	2	2	2	2	2	2	4	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Root crop	Mild	12M	2	4	4	4	4	1	1	1	1	4	4	4	4	2	2	2	1	1	1	1	2	2	4	4	2	4	4	
Root crop	Cool	12M	2	4	4	4	4	1	1	1	1	4	4	4	4	2	2	2	1	1	1	1	2	2	4	4	2	4	4	
Tomato	Mild	12M	0	0	0	0	0	4	4	4	4	0	0	0	0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	
Tomato	Cool	12M	0	0	0	0	0	4	4	4	4	0	0	0	0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	
Raw greens	Mild	12M	2	4	4	4	4	4	4	4	4	4	4	4	4	1	1	1	1	1	1	1	1	1	2	2	2	2	2	
Raw greens	Cool	12M	2	4	4	4	4	4	4	4	4	4	4	4	4	1	1	1	1	1	1	1	1	1	2	2	2	2	2	
Raw greens	Mild	12M	2	4	4	4	4	4	4	4	4	4	4	4	4	1	1	1	1	1	1	1	1	1	2	2	2	2	2	
Raw greens	Cool	12M	2	4	4	4	4	4	4	4	4	4	4	4	4	1	1	1	1	1	1	1	1	1	2	2	2	2	2	

Cooked greens	Mild	12M	2	4	4	4	1	1	1	1	1	4	4	2	2	2	2	2	2	2	2	2	2	4	4	4
Cooked greens	Cool	12M	2	4	4	4	4	1	1	1	1	4	4	2	2	2	2	2	2	2	2	2	4	4	4	4

Crop category represents different crop families expected by consumers in their vegetable boxes. Tomatoes, carrots, and potatoes were so strongly expected that they were a separate category.

Cold climate referred to the Lorraine and Normandy area (max and min T in summer and winter), and the mild climate referred to Brittany, Pays de La Loire, and Centre-Val de Loire (max and min T in summer and winter).

9M: marketing from April to December excluding winter storage crops; 12M: marketing through the whole year including winter storage crops.

A “crop share” is the quantity of crop required for one vegetable box (mean between the 10 microfarms used to calibrate the model and used in SM3).

Marketing criteria were checked at every iteration of sub-model 3 (SM3) to guarantee satisfactory diversity and quantity of crops throughout the selling period, which is key for customer satisfaction and loyalty. Minimal number of shares per month is a quantity criterion, whereas minimal number of crops per crop category (per month or per trimester) is a diversity criterion.

1 **Appendix B.** Sensitivity analysis of the MERLIN model

3 *Method*

5 This sensitivity analysis was carried out to identify the effect of the parameters on the model
 6 outputs for an annual workload of 2,500h. All parameters were not involved in all scenarios;
 7 therefore, the effect of each parameter was analyzed only for the scenarios in which it was
 8 involved. Simulations were run increasing or decreasing each parameter value by 10%. The
 9 same number of simulations was run as in the paper. For each change in the parameter value,
 10 the average income was compared with the mean income of the simulations without change
 11 (Figs. B.1 and B.2).

12 **Table B.1.**

13 Parameters considered in the sensitivity analysis from sub-models SM1 and SM2.

Name	Description	Initial value	Alternative values ($\pm 10\%$)		Unit	Scenarios used for analysis
Ym	Mean of the intercept of the model estimating the yield (Y) per square meter	0.375	0.4125	0.3375	log (kg m ⁻²)	All
Y1	Mean of the fixed effect of “motorized labor only for tillage” on Y	0.4811	0.52921	0.43299	log (kg m ⁻²)	Mi
Y2	Mean of the fixed effect of “manual labor only” on Y	0.3216	0.35376	0.28944	log (kg m ⁻²)	Bi
Yf	Standard deviation of the random effect of farms on Y	0.1352	0.14872	0.12168	log (kg m ⁻²)	All
Wm	Mean of the intercept of the model estimating production workload (Wp) per square meter	3.0853	3.39383	2.77677	log (min m ⁻²)	All
Wm1	Mean of the fixed effect of “motorized labor only for tillage” on Wp	-0.3657	-0.40227	-0.32913	log (min m ⁻²)	Bi
Wm2	Mean of the fixed effect of “manual labor only” on Wp	-0.1159	-0.12749	-0.10431	log (min m ⁻²)	Mi
Wm3	Mean of the fixed effect of “low-input practices” on Wp	0.4707	0.51777	0.42363	log (min m ⁻²)	Bi and Mi
Wm4	Mean of the fixed effect of “self-built equipment” on Wp	0.5139	0.56529	0.46251	log (min m ⁻²)	LS
Wf	Standard deviation of the random effect of farms on Wp	0.2062	0.22682	0.18558	log (min m ⁻²)	All
Yc	Standard deviation of the random effects of crops on Y*	0.6978	0.76758	0.62802	Log (kg m ⁻²)	All
Wc	Standard deviation of the random effects of crops on Wp**	0.4623	0.50853	0.41607	Log (min m ⁻²)	All

15 *Initial value of the impact of each crop on Y was increased or decreased, respectively, by 10%. **Initial value of
 16 the impact of each crop on Wp was increased or decreased, respectively, by 10%. Mi, manual; Bi, bio-intensive.
 17

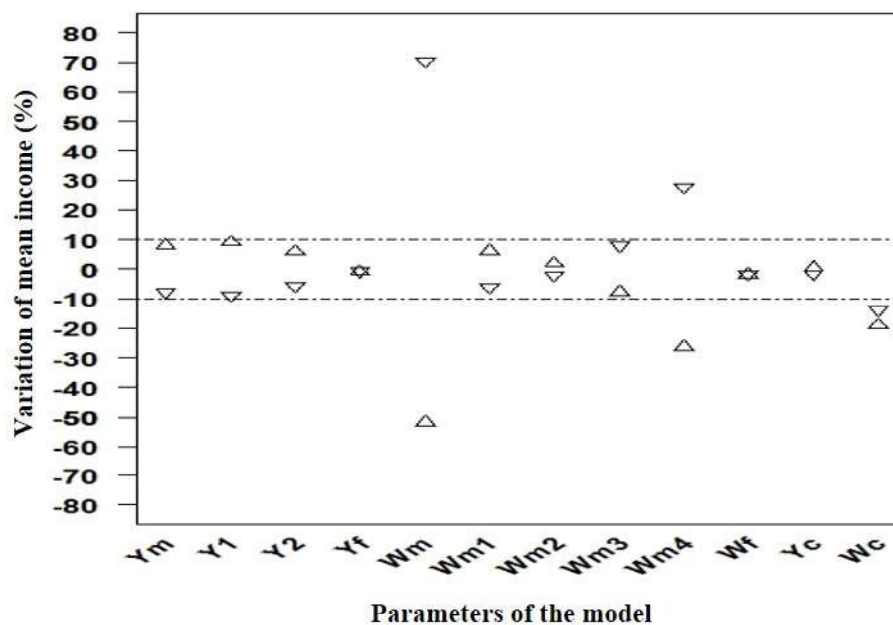
18 **Table B.2.**
 19 Other parameters of the model considered in the sensitivity analysis.
 20

Name	Description	Initial_value	Alternative values	Unit	Scenarios used for analysis
P	Crop prices	see Table 2		EUR kg ⁻¹	All
MCI _t	Maximal cropping intensity in tunnels	see Table 5		%	All
MCI _o	Maximal cropping intensity outdoors	see Table 5		%	All
SF _t	Share of footpaths in the tunnels UAA	20%		%	All
SF _o	Share of footpaths in the outdoors UAA	35%		%	All
VC	Variable costs	see Table 7		%	All
FC	Fixed costs, social security and insurance	see Table 7	±10% of the value of all parameters	€ per farm	All
FS	Fixed subsidies	see Table 7		€ per farm	All
FM	Subsidies per square meter of UAA	see Table 7		€ m ⁻²	All
FI	Fixed investment per farm	see Table 8		€ per farm	HS and LS
LI	Initial investment per square meter of land	see Table 8		€ m ⁻²	HS and LS
TI	Initial investment per square meter of tunnels	see Table 8		€ m ⁻²	HS and LS
SS	Additional subsidies for setting up per unit area of land	see Table 8		€ m ⁻²	HS and LS

21 HS, high-cost setup; LS, low-cost of setup; UAA, utilized agricultural area.

22

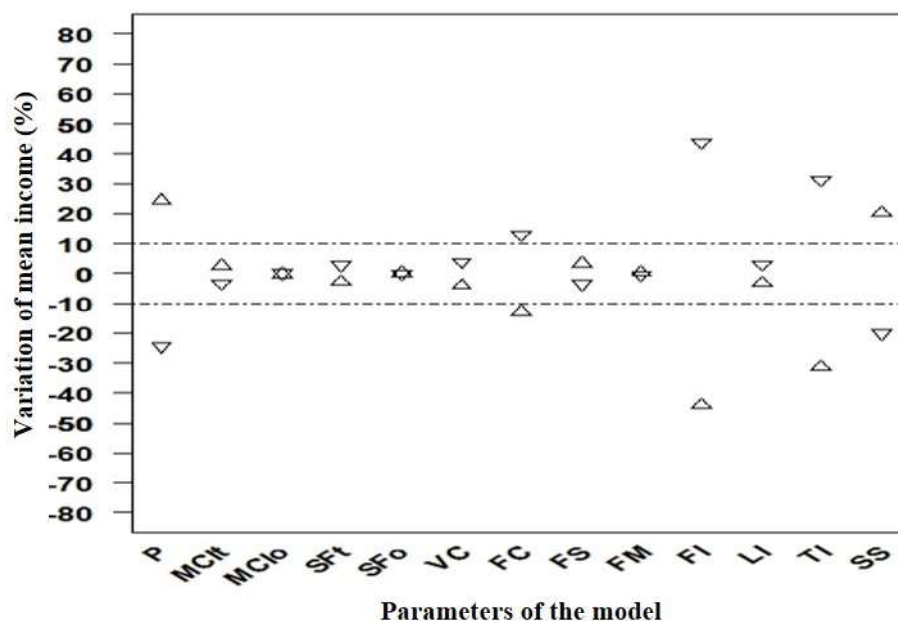
23 Results



24

25 **Fig. B.1.** Variation in mean income caused by variation of parameters from sub-models 1 and 2 with a workload
 26 of 2,150 h. Triangles represent a 10% increase; upside-down triangles represent a 10% decrease. Only scenarios
 27 in which the parameters were involved are presented.

28



29
 30 **Fig. B.2.** Variation in mean income caused by variations of other parameters. Triangles represent a 10% increase;
 31 upside-down triangles represent a 10% decrease. Only scenarios in which the parameters were involved are
 32 presented.

33

34 ***Short note about the impact of prices on incomes***

35 A variation of 10% of crops prices can lead to more than 20% of variation in income because
 36 mean incomes have absolute lower values than gross sales (once fixed costs and variable costs
 37 have been subtracted to gross sales). A given variation in gross sales is therefore relatively
 38 bigger when considered at the income level. For example, if gross sales are 30,000 EUR, an
 39 increase of 10% will lead to 33,000 EUR (+3,000 EUR) of gross sales. If we assume 16,000
 40 EUR of fixed and variable costs, the income will raise from 14,000 EUR (30,000-16,000) to
 41 17,000 EUR (33,000-16,000) which represents an increase of around 21% in income: (17,000-
 42 14,000)/14,000.