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Review

Decision Support Tools and Strategies to Simulate Forest Landscape Evolutions Integrating Forest Owner Behaviour: A Review from the Case Studies of the European Project, INTEGRAL

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Sustainability **2017**, *9*, 599; doi:10.3390/su9040599 www.mdpi.com/journal/sustainability

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Academic Editor: Marc A. Rosen
Received: 16 December 2016; Accepted: 7 April 2017; Published: 13 April 2017

Abstract: For forest sustainability and vulnerability assessment, the landscape scale is considered to be more and more relevant as the stand level approaches its known limitations. This review, which describes the main forest landscape simulation tools used in the 20 European case studies of the European project "Future-oriented integrated management of European forest landscapes" (INTEGRAL), gives an update on existing decision support tools to run landscape simulation from Mediterranean to boreal ecosystems. The main growth models and software available in Europe are described, and the strengths and weaknesses of different approaches are discussed. Trades-offs between input efforts and output are illustrated. Recommendations for the selection of a forest landscape simulator are given. The paper concludes by describing the need to have tools that are able to cope with climate change and the need to build more robust indicators for assessment of forest landscape sustainability and vulnerability.

Keywords: decision support system; forest landscape; indicators; sustainability; wood resource; risk evaluation; storm; fire; diseases; forest management; forest owner behaviour

1. Introduction

For forest sustainability assessment and land use planning, landscape approaches are considered to be more and more relevant [1]. For the most part, the management unit level is only partially informative when evaluating ecosystem services and ecosystem processes that can be affected on a larger scale [2]; therefore, there is a need for tools that can cope with landscape heterogeneity and varied forest management. The temporal succession of wood harvesting from one stand to another in a highly fragmented [3] forest landscape generates heterogeneity in ages and structure that cannot be easily extrapolated from the observation of a single stand. These temporal dynamics can affect a large set of parameters, from the wood production per year (affecting market and industry) to the biodiversity of these landscapes. In addition, sustainability monitoring requires a large set of indicators [4] which comprise economic, social and ecological components. Tools exist to monitor these factors at a stand level, but many of them, such as Shannon diversity [5], recreation [6] or the employment index [7] make sense only when large areas are taken into account.

These considerations lead to the development of a land use planning concertation process and an increasing demand for landscape foresight studies. Because forest is a significant part of forest landscapes [4] in many regions, the selection of the most appropriate tools to model the evolution of various landscape parameters associated to forests over time, under many types of constraints, is highly relevant. The EU project, INTEGRAL [8], involving 21 research groups from 13 European countries, assessed how different policies influence forest manager silviculture, and how these policies would influence the provision of ecosystem services in a 30–50-year time frame. In order to do this, forest landscape evolution was modelled using one or two large representative case study areas per country, where, in a thus far unprecedented collaboration by social and natural scientists, sets of policy scenarios have been developed and translated into forest owner specific management. An important part of the research was to identify each region's most relevant forest ecosystem service and to design and/or implement appropriate quantitative indicators for benchmarking ecosystem service provision in the forest growth scenarios using the most appropriate and up-to date growth models and decision support tools.

Considering that the INTEGRAL project case studies cover a representative set of socio-economical and forest contexts in Europe [9], the project offers an excellent overview of all the technical options for carrying out such simulations that were available in 2015 throughout Europe. Rather than presenting the results of each case study [10–13], or comparing the results of the landscape simulation qualitatively [9] throughout the regions, **this paper focuses on the modelling tools and datasets used during the INTEGRAL project to carry out simulations on a representative set of 20 European forest landscapes so that we can illustrate the strengths and limits of various approaches and tools available in Europe**. It provides above all an overview of the characteristics of stand growth models and decision support tools that can be used for such landscape simulations and can explain the consequences of the choices in terms of portability from one region to the other. The detailed inputs and outputs allow the reader to make appropriate choices when running similar simulations within different contexts.

2. Descriptions of the Decision Support System (DSS) Used for Landscape Simulation within INTEGRAL Case Studies

2.1. The Simulated Forest Management Programmes

In order to obtain a representative assessment of the potential consequences of political decisions on forest landscapes, different forest management programmes were simulated under various political scenarios during 30–97 year period [11] in the 20 INTEGRAL case studies (Figure 1): two in Sweden (VIL and HEL), two in Lithuania (ZEM and SUV), two in Ireland (WES and NEW), one in The Netherlands (SEV), two in Germany (UPP and MUN), two in Slovakia (KYS and POD), one in France (PON), two in Bulgaria (TET and YUN), three in Italy (ASI, MOL and ETN) and three in Portugal (SOU, LEI, CHA). Detailed descriptions about the case studies are available in [9] and Table 1 provides basic information about these case study areas, such as: total area (from 600 to 697,000 ha), forest area (from 501 to 330,000 ha), number of tree species in the area (from 5 to 29) and main trees species names.

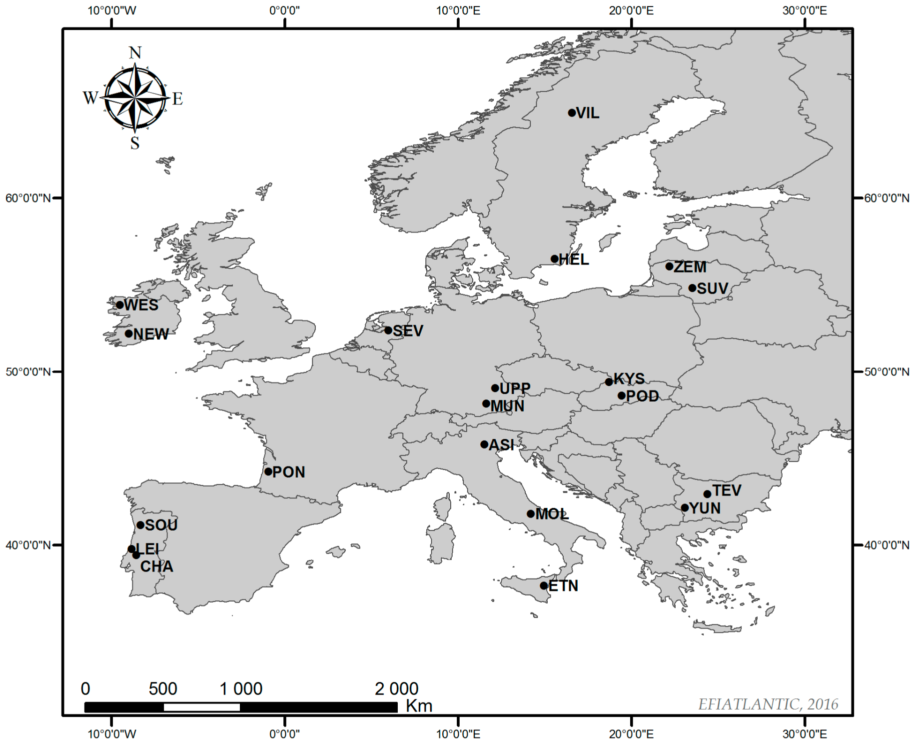

Figure 1. Geographic location of all INTEGRAL case study areas. The full case studies names are available in Table 1.

Table 1. Basic information about the case study areas covered by the INTEGRAL project. Countries names are ordered alphabetically. Species codes are specified in the abbreviation list.

Country	Case Study Area (CSA)	CSA Acronym	Forest Region in Europe	Latitude	Longitude	Total Area (ha)	Forest Area (ha)	Number of Trees Species in CSA	Main Tree Species (>10% of Volumes in the Area)
Bulgaria	Teteven	TET	E	42°55′N	24°25′E	69,700	47,812	29 (NFI)	FASY, CAOR, QUCE, PISY
Bulgaria	Yundola	YUN	E	42°01′N	23°06′E	5211	4750	13 (NFI)	ABAL, FASY
France	Pontenx	PON	CW	44°12′N	00°55′W	101,000	86,000	8	PIPI, QUPY, QURO
Germany	Munich South	MUN	CW	48°08′N	11°34′E	60,000	43,200	38 (NFI)	PIAB, PISY, FASY
Germany	Upper Palatinate	UPP	CW	49°01′N	12°05′E	300,000	159,000	36 (NFI)	PIAB, FASY
Ireland	Newmarket	NEW	NW	52°12′N	09°00′W	187,820	28,000	15	PISI, PIAB, PICO, PISY, LADE, LAKA, PSME, QUPE, FASY
Ireland	Western Peatlands	WES	NW	53°48′N	09°31′W	1,060,000	116,000	16	PISI, PIAB, PICO, PISY, LADE, LAKA, PSME, QUPE, FASY
Italy	Asiago	ASI	S	45°52′N	11°31′E	103,000	2350	3	PIAB, ABAL, FASY
Italy	Etna	ETN	S	37°45′N	14°59′E	25,300	19,500	3	ABAL, QUCE, *Fagus* spp.
Italy	Molise	MOL	S	41°40′N	14°15′E	600	501	3	QUPU, QUIL, PINI plantations, ABAL native forests
Lithuania	Suvalkija	SUV	E	54°45′N	23°30′E	66,000	36,785	15	PISY, PIAB, BEPU, BEVE, ALGL
Lithuania	Zemaitija	ZEM	E	55°59′N	22°15′E	37,900	13,674	16	PISY, PIAB, BEPU, BEVE
The Netherlands	South East Veluwe	SEV	W	52°13′N	5°58′E	8000	6000	23	FASY, PISY, PSME, QURO
Portugal	Chamusca	CHA	S	39°21′N	8°29′W	74,600	21,978	4	EUGL, PIPI, PIPIN, QUSU
Portugal	Leiria	LEI	S	39°45′N	8°48′W	75,200	10,768	1	PIPI
Portugal	Sousa	SOU	S	41°04′N	8°15′W	48,900	14,832	3	EUGL, PIPI
Slovakia	Kysuce	KYS	E	49°22′N	18°44′E	98,222	55,609	5	PIAB, FASY, ABAL, *Quercus* spp., PISY
Slovakia	Podpol'anie	POD	E	48°34′N	19°30′E	21,255	10,627	5	PIAB, FASY, ABAL, *Quercus* spp., PISY
Sweden	Helgeå	HEL	N	56°25′N	15°42′E	120,000	96,000	5	PIAB, PISY
Sweden	Vilhelmina	VIL	N	64°55′N	16°35′E	850,000	330,000	5	PISY, PIAB

Species names are coded using the first two letters of species and genus names (except for *Pinus pinea* L. (PIPIN)). It includes *Abies alba* Mill. (ABAL); *Acer pseudoplatanus* L. (ACPS); *Alnus glutinosa* (L.) Gaertn (ALGL); *Alnus incana* (L.) Moench (ALIN); *Betula pubescens* Ehrh. (BEPU); *Betula pendula* Roth. (BEPE); *Carpinus betulus* L. (CABE); *Carpinus orientalis* Mill. (CAOR); *Castanea sativa* Mill. (CASA); *Eucalyptus globulus* Labill. (EUGL); *Fagus sylvatica* L. (FASY); *Fraxinus excelsior* L. (FREX); *Ilex aquifolium* L. (ILAQ); *Juniperus communis* L. (JUCO); *Larix decidua* Mill. (LADE); *Larix kaempferi* (Lamb.) Carrière (LAKA); *Picea abies* (L.) H.Karst. (PIAB); *Picea sitchensis* (Bong.) Carrière (PISI); *Pinus contorta* Douglas ex Loudon (PICO); *Pinus nigra* J.F.Arnold (PINI); *Pinus pinaster* Aiton (PIPI); *Pinus sylvestris* L. (PISY); *Populus tremula* L. (POTR); *Pseudotsuga menziesii* (Mirb.) Franco (PSME); *Quercus cerris* L. (QUCE); *Quercus ilex* L. (QUIL); *Quercus petraea* (Matt.) Liebl. (QUPE); *Quercus pubescens* Willd. (QUPU); *Quercus pyrenaica* Willd. (QUPY); *Quercus robur* L. (QURO); *Quercus rubra* L. (QURU); *Quercus suber* L. (QUSU); *Robinia pseudoacacia* L. (ROPS); *Salix caprea* L. (SACA); *Sorbus aucuparia* L. (SOAU); *Tilia cordata* Mill. (TICO).

Various forest management schemes were implemented in the diverse forest stands of the case studies, as some of the political scenarios supposed massive changes in priorities, like, for example, an increase in wood for biomass and a reduction in wood production for timber at horizon 2050. All the forest management options are detailed in the project WIKI [14] and classified according to four types in Biber P. et al. [9]: the business as usual, the near business as usual, the less intensive and the more intensive scenarios. For each of them, the species, the silvicultural practices and the thinning regimes are specified. In each case study, between 3 and 7 forest management schemes were simulated for at least 30 years.

2.2. The Evolution Engines and Landscape Simulation Tools

Assuming future changes in forest management occur at the stand level—given that it is the forest owner who decides how to manage his property—the challenge is to assess the evolution of ecosystem services and risk indicators on the landscape scale, timber production in particular, while combining all the different types of behaviour. Thus, the first constraint was to identify tools able to quantify wood production in forest stands [15] that are similar to those present in the studied areas.

The second constraint was to be able to use these tools throughout large zones made up of thousands of different stands. Therefore, the INTEGRAL partners selected the most appropriate solutions already existing within the forest domain to evaluate timber and biomass production over time (shown in Tables 2 and 3 and described hereunder). In order to perform such analyses on a landscape scale, both growth models (stand level—Table 3) and landscape simulation tools (Table 2) (which can be embedded in the same software) were used in each case study.

Table 2. Species and landscape simulation tools (Decision Support System (DSS)) and growth models used by each INTEGRAL case study area (CSA). Species codes are specified in the abbreviation list.

CSA Acronym	Species Simulated	Growth Model (GM) Name/Number of GM Used	DSS for Pooling Results at the Landscape Level	Modelled Area (ha)	Spatially Explicit (Map of Stands)	Landscape Level Tools (e.g., Constrains, Additional Rules, Optimisation, etc.)
TET	FASY, PISY	SIBIYLA/1	SIBYLA [16]	10,148 (2671 stands)	sampling plots map	Felling volume per stand is optimized (not to exceed the natural growth)
YUN	ABAL, FASY	SIBYLA/1	SIBYLA	3733 (861 stands)	sampling plots map	Felling volume per stand is optimized (not to exceed the natural growth)
PON	PIPI, QURO	Lemoine [17]; Fagacées [18]/2	SIMMEM in Capsis [19,20]	66,700 (17,792 stands)	yes	Total harvested area per year (10%). Allocate suitable sites for specific for FMP
MUN	ABAL, FASY, LADE, PIAB, PISY, PSME, QUPE/QURO, ALGL; Grouped Species: ACPS, FREX, TICO; PISY	SILVA/1	SILVA [21]	40,000 (746 strata)	no	no
UPP	ABAL, FASY, LADE, PIAB, PISY, PSME, QUPE/QURO, ALGL; Grouped Species: ACPS, FREX, TICO; PISY	SILVA/1	SILVA	160,000 (927 strata)	no	no
NEW	PISI, PIAB, PICO, PISY, LADE, LAKA, PSME, QUPE, FASY	British Yield tables/9	REMSOFT Woodstock [22]	165,000	yes	Exogenous landscape optimisation
WES	PISI, PIAB, PICO, PISY, LADE, LAKA, PSME, QUPE, FASY	British Yield tables/10	REMSOFT Woodstock	116,000	yes	Landscape optimisation
ASI	PIAB, ABAL, FASY	EFISCEN [23,24]/1	Excel	2350 (230 plots, 160 stands)	no	no
ETN	ABAL, QUCE, *Fagus* spp.	EFISCEN/1	Excel	19,000 (35 plots, 15 stands)	no	no
MOL	QUPU, QUIL, PINI plantations, ABAL native forests	EFISCEN/1	Excel	501 (50 plots, 30 stands)	no	no
SUV	PISY, PIAB, BEPU, POTR, ALGL, ALIN, QURO, FREX	Kupolis/1	Kupolis [25] in combination with ArcGIS	36,785 (18,574 stands)	yes (strata from sampling plots)	Final felling budget per owner is optimized
ZEM	PISY, PIAB, BEPU, POTR, ALGL, ALIN, QURO, FREX	Kupolis/1	Kupolis in combination with ArcGIS	13,674 (7745 stands)	yes (strata from sampling plots)	Final felling budget per owner is optimized
SEV	ABAL, ACPS, BEPE, CABE, CASA, FASY, ILAQ, JUCO, LADE, PIAB, PISI, PINI, PISY, PRAV, PSME, QUPE, QURO, QURU, FRAL, ROPS, SACA, SOAU, TICO	LandClim logistic curves/23	LandClim [26,27]	6000 (30 × 30 m pixels, 27,000 cohorts)	Yes	Including spatial interactions due to disturbances, management, dispersal

Table 2. *Cont.*

CSA Acronym	Species Simulated	Growth Model (GM) Name/Number of GM Used	DSS for Pooling Results at the Landscape Level	Modelled Area (ha)	Spatially Explicit (Map of Stands)	Landscape Level Tools (e.g., Constrains, Additional Rules, Optimisation, etc.)
CHA	EUGL, PIPI, PIPIN, QUSU	Globulus 3.0, GYMMA, Pinaster, PBIRROL, PINEA, SUBER/6	SUBER is a separate software. Other GM in StandsSIM in SADfLOR [28–30]	19,526 (5681 stands)	No	no
LEI	PIPI	MLN model/1	Separate software	7097 (404 stands)	No	no
SOU	EUGL, PIPI, CASA	Globulus 3.0, GYMMA, Pinaster, PBIRROL, PINEA, CASTANEA/5	Chesnut: yield tables in a different platform Other GM in StandsSIM in SADfLOR	14,388 (1972 stands)	No	no
KYS	ABAL; FASY; PIAB; PISY; *Quercus* sp. Other species are modelled on the basis of similarity to some of the main tree species.	SIBYLA/1	SIBYLA	56,609 (315 stands)	strata from sampling plots	no
POD	ABAL; FASY; PIAB; PISY; *Quercus* sp. Other species are modelled on the basis of similarity to some of the main tree species.	SIBYLA/1	SIBYLA	10,627 (378 stands)	strata from sampling plots	no
HEL	PIAB, PISY, *Betula* spp.	Heureka [31]/1	DSS (including individual tree models)	96,000 ha	No	no
VIL	PISY, PIAB, *Betula* spp., POTR, PICO	Heureka/1	DSS with optimization	330,000 (36,114 stands)	No	Stands classified on different management groups

Includes *Abies alba* Mill. (ABAL); *Acer pseudoplatanus* L. (ACPS); *Alnus glutinosa* (L.) Gaertn (ALGL); *Alnus incana* (L.) Moench (ALIN); *Betula pubescens* Ehrh. (BEPU); *Betula pendula* Roth. (BEPE); *Carpinus betulus* L. (CABE); *Carpinus orientalis* Mill. (CAOR); *Castanea sativa* Mill. (CASA); *Eucalyptus globulus* Labill. (EUGL); *Fagus sylvatica* L. (FASY); *Fraxinus excelsior* L. (FREX); *Ilex aquifolium* L. (ILAQ); *Juniperus communis* L. (JUCO); *Larix decidua* Mill. (LADE); *Larix kaempferi* (Lamb.) Carrière (LAKA); *Picea abies* (L.) H.Karst. (PIAB); *Picea sitchensis* (Bong.) Carrière (PISI); *Pinus contorta* Douglas ex Loudon (PICO); *Pinus nigra* J.F.Arnold (PINI); *Pinus pinaster* Aiton (PIPI); *Pinus pinea* L. (PIPIN); *Pinus sylvestris* L. (PISY); *Populus tremula* L. (POTR); *Prunus avium* L. (PRAV); *Pseudotsuga menziesii* (Mirb.) Franco (PSME); *Quercus cerris* L. (QUCE); *Quercus ilex* L. (QUIL); *Quercus petraea* (Matt.) Liebl. (QUPE); *Quercus pubescens* Willd. (QUPU); *Quercus pyrenaica* Willd. (QUPY); *Quercus robur* L. (QURO); *Quercus rubra* L. (QURU); *Quercus suber* L. (QUSU); *Frangula alnus* L. (FRAL); *Robinia pseudoacacia* L. (ROPS); *Salix caprea* L. (SACA); *Sorbus aucuparia* L. (SOAU); *Tilia cordata* Mill. (TICO).

Table 3. Growth models used by the INTEGRAL case study areas. Species codes are specified in the abbreviation list.

Growth Model (GM) Name/DSS	GM Spatial Structure (Basic Spatial Unit)	GM Type	Distance Dependence	Time Step	Stochasiticity	Stand Composition	Stand Form	Species (GM Calibrated)	Mortality	Hazards	Global Change	Optimisation
SIBYLA/SIBYLA software	individual	empirical	yes	1	yes	mixed	uneven-aged	ABAL, FASY, PIAB, PISY, QUPE, QURO	yes	yes	yes	no
Fagacées/SIMMEM in Capsis	individual	empirical	yes	3	no	pure	even-aged	QUPE	yes	no	no	no
Lemoine Model-PP1/SIMMEM in Capsis	stand	empirical	no	1	no	pure	even-aged	PIPI	no	no	no	no
SILVA	individual	empirical	yes	1–5	yes	mixed	even- and uneven-aged	ABAL, FASY, LADE, PIAB, PISY, PSME, QUPE, QURO, ALGL; Grouped Species: ACPS, FREX, TICO	yes	no	yes	no
Remsoft Woodstock	stand	yield table	no	1	no	pure	even-aged	PISI, PIAB, PICO, PISY, LADE, LAKA, PSME, QUPE, FASY	yes	no	no	yes
EFISCEN	stand	matrix model	no	5	no	pure	even-aged and coppice forests	PIAB, ABAL, FASY, ABAL, QUCE, QUPU, QUIL, PINI, ABAL, *Fagus* spp.	yes	yes	no	no
Kupolis	stand	empirical	no	5	no	mixed	uneven-aged	PISY, PIAB, BEPU, BEVE, POTR, ALGL, ALIN, QURO, FREX	yes	no	no	yes
ForClim in LandClim	stand	process based	no	10	yes	mixed	uneven-aged	ABAL, ACPS, BEPE, CABE, CASA, FASY, ILAQ, JUCO, LADE, PIAB, PISI, PINI, PISY, PRAV, PSME, QUPE, QURO, QURU, FRAL, ROPS, SACA, SOAU, TICO	yes	yes	yes	no
Heureka	individual	empirical	yes	5	no	mixed	even- and uneven-aged	PIAB, PISY, *Betula* spp., *Quercus* spp., *Fagus* spp.	yes	yes	yes	yes

Table 3. *Cont.*

Growth Model (GM) Name/DSS	GM Spatial Structure (Basic Spatial Unit)	GM Type	Distance Dependence	Time Step	Stochasiticity	Stand Composition	Stand Form	Species (GM Calibrated)	Mortality	Hazards	Global Change	Optimisation
Globulus 3.0/StandsSIM in SADfLOR	stand	empirical	no	1	no	pure	even-aged	*Eucalyptus* spp.	yes	no	no	no
GYMMA/StandsSIM in SADfLOR	stand	empirical	no	1	no	pure	uneven-aged	*Eucalyptus* spp.	yes	no	no	no
Pinaster/StandsSIM in SADfLOR	stand	empirical	no	1	no	pure	even-aged	PIPI	yes	no	no	no
PBIRROL/StandsSIM in SADfLOR	stand	empirical	no	1	no	pure	uneven-aged	PIPI	yes	no	no	no
PINEA/StandsSIM in SADfLOR	stand	yield table	no	1	no	pure	even-aged	PIPIN	yes	no	no	no
SUBER/StandsSIM in SADfLOR	stand	empirical	no	1	no	pure	even- and uneven-aged	QUSU	yes	no	no	no
MNLmodel	stand	empirical	no	1	no	pure	even-aged	PIPI	yes	no	no	no
CASTANEA	stand	yield table	no	5	no	pure	even-aged	CASA	yes	no	no	no

Includes *Abies alba* Mill. (ABAL); *Acer pseudoplatanus* L. (ACPS); *Alnus glutinosa* (L.) Gaertn (ALGL); *Alnus incana* (L.) Moench (ALIN); *Betula pubescens* Ehrh. (BEPU); *Betula pendula* Roth. (BEPE); *Carpinus betulus* L. (CABE); *Carpinus orientalis* Mill. (CAOR); *Castanea sativa* Mill. (CASA); *Eucalyptus globulus* Labill. (EUGL); *Fagus sylvatica* L. (FASY); *Fraxinus excelsior* L. (FREX); *Ilex aquifolium* L. (ILAQ); *Juniperus communis* L. (JUCO); *Larix decidua* Mill. (LADE); *Larix kaempferi* (Lamb.) Carrière (LAKA); *Picea abies* (L.) H.Karst. (PIAB); *Picea sitchensis* (Bong.) Carrière (PISI); *Pinus contorta* Douglas ex Loudon (PICO); *Pinus nigra* J.F.Arnold (PINI); *Pinus pinaster* Aiton (PIPI); *Pinus pinea* L. (PIPIN); *Pinus sylvestris* L. (PISY); *Populus tremula* L. (POTR); *Prunus avium* L. (PRAV); *Pseudotsuga menziesii* (Mirb.) Franco (PSME); *Quercus cerris* L. (QUCE); *Quercus ilex* L. (QUIL); *Quercus petraea* (Matt.) Liebl. (QUPE); *Quercus pubescens* Willd. (QUPU); *Quercus pyrenaica* Willd. (QUPY); *Quercus robur* L. (QURO); *Quercus rubra* L. (QURU); *Quercus suber* L. (QUSU); *Frangula alnus* L. (FRAL); *Robinia pseudoacacia* L. (ROPS); *Salix caprea* L. (SACA); *Sorbus aucuparia* L. (SOAU); *Tilia cordata* Mill. (TICO).

2.3. Forests Growth Models: The Key Evolution Engines

The information in Table 3 shows that landscape simulations can be based on all types of growth models [32,33]:

- The yield tables (included in REMSOFT, PINEA and CASTANEA models) are derived from equations, from data collection in the field or from stem analysis. These tables provide year-by-year growing stock value and harvested volumes for a given thinning regime. The number of yield tables needed depends on a combination of site index and thinning regime in a given area. This tool is robust and appropriate for a very standard management scheme and for homogenous sites with low fertility variation.
- The stand empirical growth models (Fagacées, Lemoine, EFISCEN, Kupolis) and matrix models (EFISCEN) comprise equations providing evolution of height and basal area (or biomass) over time for a forest stand. They can be used to compare the impact of various thinning regimes.
- The individual tree growth models can cope with a large diversity of thinning regimes providing outputs related to growth and tree shape. These models are either tree distance independent (Heureka, Pinaster, PBIRROL, SUBER and MNL) or tree distance dependent (SIBYLA, SILVA). Therefore, in the former case, the models will provide the same result whatever the shape of the parcel or the tree distribution within the stand; whereas in the latter uneven aged stands and differences based on initial stand structure or parcel shapes can be simulated.
- The latest developments in modelling allow a combination of growth models and process based (LandClim) models to be used. These can theoretically simulate the evolution of a stand whatever thinning regime is applied, based on the competition between trees, climate and site characteristics. Recent empirical growth models, such as SIBYLA, can also take climate change into account by adjusting the site index according to climatic variables, rather than describing the light and water processes.

2.4. Specific Growth Model Characteristics Required for Certain Scenarios

The models listed in Table 3 have some specific parameters that improved the simulations for each region. However, while some of them are able to integrate parameters to make accurate predictions, others only function with basic rules.

2.4.1. Mortality

Most of the models integrate tree mortality, which is observed in any stand when the competition between trees is too high, producing more realistic simulations of stands, especially when some of the management schemes result in unmanaged stands or very high stocking. However, one model, Lemoine does not provide mortality. This is due to the fact that it was developed for maritime pine (*Pinus pinaster* Aiton) stands in a region with very intensive management for which thinning practices extract unhealthy trees faster than natural mortality can, making it impossible to use National Forest Inventory (NFI) data to set up realistic self-thinning curves [34]. Therefore, for Lemoine, a workaround was found to define a thinning regime in unmanaged stands similar to natural mortality, based on self-thinning curves from Portugal [35].

2.4.2. Hazards

Only three models (SIBYLA, EFISCEN and LandClim) used for landscape simulations integrate hazards such as fire, snow and windstorm. Table 3 reveals that in a list of 17 growth models, only four are able to simulate damages in a realistic way. Some of these tools include a ratio of damages in mortality (Heureka) assuming that some of the dead trees result from competition and some, from other damaging agents. Risks can be integrated using a non-deterministic tool if the same scenarios are run many times under a certain probability of damages [36]. This implies that for a given initial state, many simulations are needed to obtain a good approximation of the potential future status of forest, adding complexity to the exercise of landscape simulation.

2.4.3. Global Change in Models

Only four models are able to consider global change impact on forest growth (SIBYLA, SILVA, ForClim and Heureka). This functionality is extremely relevant for foresight studies that assess landscape evolution over decades, given the significant changes in climate that are expected in the next 30 years. Climate studies show that while the mean temperature of the earth is expected to increase significantly, uncertainty at local level [37] remains very high; thus the accuracy of prediction of the stand evolution induced by the climate change is partially lost due to imprecise climate forecasting on a period of 30–50 years. Moreover, if only past data are used (as for cases studies MUN and UPP), the benefit of having a climate responsive model is low, but the improvement in accuracy of regional weather data projections in the coming years will mean that these models will become increasingly useful, even with the additional layer of complexity induced by climate datasets.

2.5. The DSS: The Integrative Tools to Run Simulation at Landscape Level

2.5.1. The Need for an Integrative Tool

In many cases, a unique software includes many growth models and can handle the aggregation of stands such as SIBYLA (used for Bulgaria and Slovakia), SILVA (used in Germany) and Kupolis (in Lithuania). In other cases, specific software is needed to make stand simulations and the DSS aggregates stand data on a landscape level; for example, Capsis, thanks to the SIMMEM add-in piloted Lemoine and Fagacées stand growth models in the Aquitaine region (France) and REMSOFT was used to integrate all the yield tables needed for the Irish case study. In all cases, the landscape is only a juxtaposition of virtual stands with no interactions, considering no edge effect and no contagions.

Table 2 clearly shows that in most INTEGRAL project case studies the simulations could not cover the whole forest area, especially when it was very large. However, on average, 92% (sd = 16%) of the forest area was modelled; meaning that the tools used were able to work with the different landscape sizes studied in all case studies. As the objective of the project was not to make a resource assessment, but to compare the evolution of forest landscape on the forest case study area through many indicators of sustainability, it was not mandatory to address 100% of the forested area in the case study. Different strategies underlay this figure, but the main reason for having some parts of landscape excluded from simulations include (i) lack of data; (ii) highly heterogeneous or fragmented areas; (iii) areas with forest structure or ownership structure having limited chance to change in the future. In addition, running simulations on a limited but representative part of the landscape is also a way to cope with a limited computing capacity as some software (especially when connected to GIS) may require computer to have a huge memory and calculation capacity not available in all organisations.

As landscape modelling is based on growth models which take into account stands or a homogenous group of stands under the same management regime (strata), each forest area is divided into homogenous groups of trees which are associated with one another to be considered as a virtual stand. Thus, decision support tools, as defined in this paper, are software able to handle a large set of forest stand data and model their evolution on the landscape level providing stand year after year (every 3, 5 or 10 years depending on which growth model was run; see Table 3). The number of stands used when running the simulations was very variable depending on the case study.

The number of stand descriptions and the forest areas were represented on the same graph (Figure 2), in order to illustrate the heterogeneity of the case studies, as well as the diverse strategies which have taken into account forest landscape size, the modelling tools used and the stand parameters available. The stand descriptions came from National Forest Inventory plots, remote sensing information and management plans, while the real case study areas came from maps. To illustrate the distance between the real information and the virtual forest run by the DSS the number of virtual stands and the modelled area in the computer system was added to Figure 2.

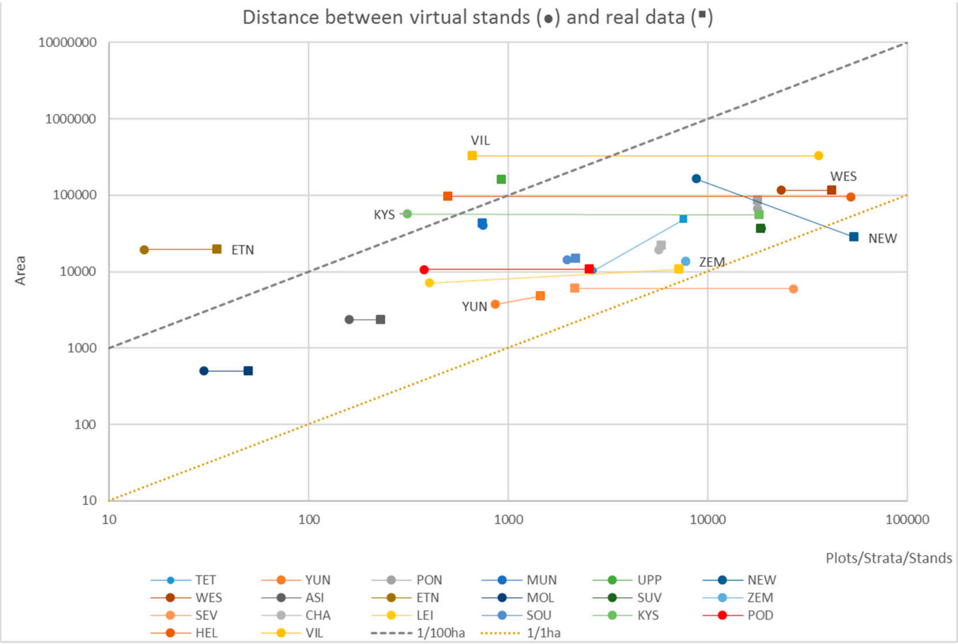

Figure 2. Distance between real area and real stand descriptions (in the field ■); and virtual stands and modelled area (in silico ●), for all case study areas of the INTEGRAL project.

As already mentioned, due to the modelled areas being close to real forest areas, most of the lines are horizontal except for NEW, where a large afforestation programme was simulated, and TET, where only part of the forest could be simulated in a realistic way.

For many of the case studies, the data available define the number of virtual stands and capture the heterogeneity of the landscape in the DSS. This is the case for YUN, UPP, MUN, SOU, CHA, PON, ZEM and SUV, and is often related to spatially explicit DSS. In the other case studies, the trend is to have less virtual stands than area inputs (ETN, MOL, ASI, KYS, POD, LEY, NEW). This can be explained by the tool used in Italy (EFISCEN) or the one used in Ireland based on strata (LandClim), which group stands with similar characteristics, significantly reducing the amount of virtual stands compared to the amount of initial plots described. On the contrary, the case study (SEV) uses a tool based on raster images and requires interpolation between plots, generating a number of virtual stands higher than the ones described.

Most of the case studies involve a level of effort in terms of sampling intensity and modelling comprising between 1 over 1 hectare and 1 over 100 hectares. The sampling intensity for ETN, HEL, UPP VIL were the highest and that for NEW was the lowest, thus showing that sampling intensity can be independent of landscape size.

Similar tools were used with data of varying accuracy. For example, the Bulgarian (TET and YUN) and Slovakian (KYS and POD) case study areas both used SIBYLA DSS, but appear very differently on Figure 2.

Therefore, the accuracy of simulations depends more on the availability of information about specific areas and landscape heterogeneity, than on the modelling tool itself.

2.5.2. Constraints Rules at the Landscape Level

In certain case studies, specific rules were applied in order to make the simulations on the landscape scale more realistic.

In France (PON-using Capsis with the SIMMEM module), a harvest constraint was applied, assuming that the forest sector is not able to mobilise more than 10% of the area.

The ForClim process-based model (for SEV in The Netherlands), directly fitted to a landscape, is the unique tool which accounts for spatial interactions due to disturbances, management and dispersal. Other especially explicit decision support tools (10) do not have neighbouring interaction.

Some of the DSS also allow to define a specific objective to reach (ratio of biomass, minimum water pollutant, max habitat suitability, etc.) and can run optimisation such as linear programming to optimise at the landscape level management options allowing to reach this goal (StandsSIM, REMSOFT, Heureka).

Despite the high simulation capacity depicted by the long list of tools in Tables 2 and 3, the very high heterogeneity of large forest landscapes is always simplified. Examples of the simplifications carried out to use the existing modelling tools are described as strategies implemented to simulate varied tree species composition and varied forest stand structures.

3. The Strategies to Cope with the Tree Species Issue

Table 1 shows that there were between one and nine major tree species (representing more than 10% of the forest cover) depending on the case study area. In many cases, the project partners were willing to simulate this species diversity: out of the twenty case studies (Table 2), more species than the major tree species were simulated ten times, the same number of species eight times, and less species than the major species were simulated twice.

In order to account for tree diversity, different strategies were applied by the DSS used; two trends can be observed: (i) by combining the growth model and the landscape simulators in one tool (SIBYLA, SILVA, Kupolis), they simulate a variety of species mixture within the stand; (ii) when the landscape simulator is only an aggregator of different growth models, several monospecific growth models or yield tables are associated into the simulator allowing a diversity of species only at the landscape scale, through a mosaic of various monospecific stands. The second option is the one chosen for Fagacées and Lemoine in Capsis (using the SIMMEM module) in the French case studies, the yields tables in REMSOFT in Ireland, EFISCEN in Excel for Italy; (iii) In Portugal mixed stands have been simulated overlapping the results of model made for pure stands in the same area, matching with the tree density of each species.

The first option (i) is also typical of the process-based model (LandClim in The Netherlands).

When specific models were lacking for a particular species, it was possible to use equations developed for another similar species in the same area; for example, the model Fagacées was developed for *Quercus petraea*, but was also used for *Quercus robur* in the Aquitaine region (France), and in Lithuania (with Kupolis) and Slovakia (with SIBYLA), secondary tree species were modelled on the basis of similarity with the main tree species.

4. The Stand Structure and Alternative Management Option Issues

Another issue faced when selecting a DSS and/or associated models is its ability to take all the management options into account in the simulations. In a foresight study such as INTEGRAL, the numerous scenarios and stakeholder consultations [11] result in a broad range of management options, from unmanaged forest to short term biomass rotation, close-to-nature forestry conversions or even the development of a previously inexistent stand mixture. Bearing this in mind, and that most growth models were designed to provide an accurate estimate of timber production under a "classical" management regime (Table 4), the range of validity of some models (i.e., context where the results remain valid) can be questioned.

For example, a growth model not able to simulate mortality induced by high stocking and natural regeneration should not be used for the modelling of unmanaged stands (this is the case of the Lemoine model). In practice, this problem has been fixed using a specific thinning regime based on self-thinning curves designed for maritime pine in Portugal [35] in unmanaged stands, where the thinned trees were counted as dead trees.

Another management option of interest for foresight studies is to evaluate the impact of change on stand structure, turning a part of the even-aged stands into uneven-aged stands, or the opposite. In the case studies, growth models, which take into account irregular stands, can also be used for regular ones, with the exception of the Portuguese models for Eucalyptus and *Pinus pinaster*, for which separate versions were developed for even-aged and uneven-aged stands. In other case studies, when no references were available, it was considered too hazardous to simulate irregular stands: Table 3 shows that only 37% of the growth models are able to account for irregular stands and that 90% of the case studies consider this option in their management choices.

A last management option of interest for the stakeholders was the installation of short rotation coppice for biomass. When such practices where not implemented, the use of empirical growth models to assess the production of very short rotation with high stocking is hazardous.

5. The Input and Output Data Sets Required to Run Landscape Simulations or Expected from the DSS

5.1. Input Data Required by the DSS

The amount of input data required varies depending on the DSS taken into consideration (Table 5), but the following three types of information are always required.

First, the initial forest landscape must be described. The applied growth models are initially designed to assess wood production; therefore, the standard parameters, which define a stand (Table 4) are species composition, basal areas or stocking, age and height. Depending on the type of growth model embedded in the DSS, these data can be required at the stand or at the tree level.

Second, site productivity must be defined. Depending on the tool, productivity can be fixed for the whole simulation or it can vary according to the climate (process based models [38] or empirical growth models dealing with climate). The required productivity can be provided directly as a combination of tree height and tree diameter at a certain age, or as the site productivity in cubic meters per hectare per year. More user-friendly approaches will compute this productivity using other variables such as soil type (or soil nutrient content and water capacity), topography (slope, upslope, aspect, elevation) distance to water course, and forest type. Some empirical growth models which take climatic impact into account, such as SIBYLA, will not deal with a constant site index, but will estimate the yearly yield depending on the climate variables provided.

A third input always required by landscape DSS is the management of each stand, usually by defining the thinning regime. According to the project strategy, a thinning regime is attributed to a given stand (taking into account the type of forest manager associated with this stand) at the beginning of the simulation and is maintained throughout the whole simulation period. The differences observed between various simulated scenarios resulted mainly from the ratios of different thinning regimes allocated to the different stands. Due to growth model characteristics (Table 4), all the thinning regimes require the classical features, such as the thinning periodicity and, in the case of even-aged stands, plantation density, and target age or target size. Yet we could observe different manners to define the thinning regimes:

- The more classical definition of the thinning regime is a calendar listing operations at a given age or the periodicity of operations. This leads to a very low flexibility depending on the heterogeneity of the environment,
- Other thinning regimes are driven by dendrometric thresholds that trigger certain actions: with SIMMEM, relative density triggers thinning and max diameter clear-cut, with ForClim, total biomass or diameter trigger thinning,
- Some of the models were also able to carry out specific optimisation by adjusting the thinning regime stand by stand to optimise a species composition or a net value depending on the site.

Table 4. Growth models used by the INTEGRAL case study areas. Variables codes are specified in the abbreviation list and are ordered alphabetically.

Growth Model (GM) Name/DSS	Modeled Variables	Derived Variables Included in the Simulation Tool	Forest Management Action (FMA) Considered during Simulation	Site Data Required by GM
SIBYLA/SIBYLA software	T_H, T_DBH	S_AGB, S_BA, S_BB, S_C, S_HTvol, S_LB, S_Dmean, S_Hmean, S_MR, S_N/ha, S_RB, S_SInd, S_Sp, S_Sp%, S_StemBAB, S_StemWB, S_Struct, S_TB, S_Age%, S_MAI, S_Dq, S_Tvol/T_AGB, T_BB, T_Coord., T_CD, T_CR, T_CL, T_DBH, T_H, T_ID, T_LB, T_LifeSta, T_RB, T_StemBAB, T_StemWB, T_TB, T_VolUB(stump), T_TBA, T_N_content (N,P,K,Ca,Mg)	Thinning regimes defined by calendar and tree target diameter	CO_2, NO_x, relative soil nutrient status, length of vegetation period, T °C mean in vegetation period, yearly T °C amplitude, amount of precipitation, soil relative moisture soil and index of site aridity/humidity
Fagacées/SIMMEM in Capsis	S_Hdom, S_Dq	S_Ddom, S_Hdom, S_N/ha, S_BA, S_Tvol, S_Tyield	Thinning regimes defined by relative density index and diameter. Clear-cut defined by max diameter	Hdom and age couple to assess site index
Lemoine Model-PP1/SIMMEM in Capsis	S_Hdom, S_Dq	S_Ddom, S_Hdom, S_N/ha, S_BA, S_Tvol, S_Tyield	Thinning regimes defined by relative density index and diameter. Clear-cut defined by max diameter	PP1: Hdom at age 40
SILVA	T_DBH, T_H, T_CR, T_CL, T_LifeSta.	S_Tvol, S_MAI, S_BA, S_N/ha, S_Ht, S_Hdom, etc. S_StandingVal, S_TValProd, S_MAIVal, etc. ShInd, the Species Profile Index, the Clark and Evens index, pair- and mark-correlation functions and others.	Thinning regimes defined by kind, strength and frequency in time	Nutrient availability, water supply and temperature related variables
Remsoft Woodstock	S_Age%, S_Sp%, S_Tyield, S_Stocking, S_ThinVol	S_DBHmean, S_Ht, S_Tvol, S_Stocking	Different FMA prescriptions are permitted/restricted in spatially determined zones	Water sedimentation risk factors (i.e., distance to watercourse, soil type, upslope contributing area and land use), soil type, elevation range
EFISCEN	S_Age%, S_Stocking, S_HTvol, S_MAI	S_Age%, S_Stocking, S_HTvol, S_MAI	Management plan defined by calendar: selective thinning, thinning, resprouting, clear-cut, preparatory cuts, seed cuts, sparse thinning, no activity	Productivity: m^3/ha/year
Kupolis	S_D%, S_Stocking, S_StandingVol, S_Age%, S_DBHmean, S_ThinVol, S_MR, S_ProdCosts, S_Tyield, S_Struct	S_Age%, S_D%, S_N/ha, S_Dmean, S_Hmean, S_Stocking, S_StandingVol, S_DBHmean, S_ThinVol, S_HTvol, S_MR, S_ProdCosts, S_Tyield, etc.	Thinning regime defined by the species composition of target trees and stocking level of the stand (thinning intensity defined by user)	Slope, soil moisture and soil nutrient content
ForClim in LandClim	S_D%, S_TB	S_C, T_TB, S_TB, S_Struct	FMA defined by biomass or diameter target. Spatial zoning of management can be defined	T °C, precipitation, soil (available N, soil depth) and topology (aspect, DEM, slope).
Heureka	T_DBH, T_H, T_LifeSta	S_RecVal, S_Cseq., S_Hab_Ind/S_HTvol, S_HTvolAssort, S_ProdCosts, S_TimbVal	Pre-commercial thinning, thinning, clear-cut, scarification, planting, fertilization	Total and Productive Area, County Code, Altitude, Latitude, SInd, Soil Moisture Code, Vegetation Type
Globulus 3.0/StandsSIM in SADfLOR	S_N/ha, S_Ddom, S_BA, S_VolUB, S_VolUB(stump)	S_MTVol, S_BAC, S_BB, S_LB, S_RB, S_StemBAB, S_StemWB, S_Dq, S_ThinVol, S_HTvol, S_C, S_ProdCosts, S_W&S	Goal: pulp, wood, energy, cork or cone production. FMA is characterized by: densities, thinning, intensity and periodicity, clear-cuts and number of rotations in the case of eucalyptus	Climatic data, S_SInd

Table 4. *Cont.*

Growth Model (GM) Name/DSS	Modeled Variables	Derived Variables Included in the Simulation Tool	Forest Management Action (FMA) Considered during Simulation	Site Data Required by GM
GYMMA/StandsSIM in SADfLOR	S_N/ha, S_Ddom, S_BA	S_MTVol, S_BAC, S_BB, S_LB, S_RB, S_StemBAB, S_StemWB, S_Dq, S_ThinVol, S_HTvol, S_C, S_ProdCosts, S_W&S	Goal: pulp, wood, energy, cork or cone production. FMA is characterized by: densities, thinning, intensity and periodicity, clear-cuts and number of rotations in the case of eucalyptus	Climatic data, S_SInd
Pinaster/StandsSIM in SADfLOR	S_Sind, S_Hdom, S_MR, S_Dmean, S_D%	S_N/ha, S_BA, S_Standing_Vol, S_MTVol, S_BB, S_LB, S_RB, S_StemBAB, S_StemWB, S_Dq, S_ThinVol, S_HTvol, S_C, S_ProdCosts, S_W&S	Goal: pulp, wood, energy, cork or cone production. FMA is characterized by: densities, thinning, intensity and periodicity, clear-cuts and number of rotations in the case of eucalyptus	Climatic data, S_SInd
PBIRROL/StandsSIM in SADfLOR	S_ThinVol, S_DBHmean, S_MR	S_BA, S_N/ha, S_StandingVol, S_MTVol, S_BB, S_LB, S_RB, S_StemBAB, S_StemWB, S_Dq, S_ThinVol, S_HTvol, S_C, S_ProdCosts, S_W&S	Goal: pulp, wood, energy, cork or cone production. FMA is characterized by: densities, thinning, intensity and periodicity, clear-cuts and number of rotations in the case of eucalyptus	Climatic data, S_SInd
PINEA/StandsSIM in SADfLOR	S_DBHmean, S_MR, S_D%	S_BA, S_N/ha, S_StandingVol, S_MTVol, S_BB, S_LB, S_RB, S_StemBAB, S_StemWB, S_Dq, S_ThinVol, S_HTvol, S_C, S_ProdCosts, S_W&S, S_Cones_yield	Goal: pulp, wood, energy, cork or cone production. FMA is characterized by: densities, thinning, intensity and periodicity, clear-cuts and number of rotations in the case of eucalyptus	Climatic data, S_SInd
SUBER/StandsSIM in SADfLOR	S_DBHmean, S_Hmean, S_Ckyield, S_MR, S_H%	S_BA, S_BAC, S_N/ha, S_StandingVol, S_BAC, S_BB, S_LB, S_RB, S_StemBAB, S_StemWB, S_Dq, S_ThinVol, S_C, S_ProdCosts, S_W&S, S_Ckyield, S_DBHmean, S_Hmean,	Goal: pulp, wood, energy, cork or cone production, except operations related to wood extraction	Climatic data, S_SInd
MNLmodel	S_N/ha, S_Hdom, S_BA	S_StandingVol, S_AGB, S_Dq, S_ThinVol, S_HTvol, S_C	Goal: pulp, wood, energy, cork or cone production	Climatic data, S_SInd
CASTANEA	S_SInd, S_Hdom, S_N/ha	S_MTVol, S_Dq, S_BA, S_StandingVol, S_C, S_Cseq., S_ThinVol, S_HTvol, S_BB, S_LB, S_RB, S_StemBAB, S_StemWB	Goal: pulp, wood, energy, cork or cone production. FMA is characterized by: densities, thinning, intensity and periodicity, clear-cuts and number of rotations in the case of eucalyptus	Climatic data, S_SInd

Variables codes use an 'S' for 'Stand' and 'T' for 'Tree': Area (A); Aboveground biomass (AGB); Age (Age%); Basal area (BA); Basal area (with bark) (BAC); Branches biomass (BB); Carbon sequestration (Cseq.); Carbon stock (C); Cones yield (Cones_yield); Coordinates (Coord.); Cork yield (Ckyield); Crow ratio (CR); Crown diameter (CD); Crown length (CL); Diameter at Breast Height (DBH); Diameter distribution (D%); Dominant diameter (Ddom); Dominant height (Hdom); Habitat suitability (Hab_Ind); Harvest timber volume (HTvol); Height (H); Height distribution (H%); Identification (ID); Leaf biomass (LB); Life status (alive/dead) (LifeSta); Mean annual volume increment (MAI); MAI value (MAIVal); Mean DBH (DBHmean); Mean diameter (Dmean); Mean height (Hmean); Merchantable volumes (MTVol); Mortality (MR); Number of trees per ha (N/ha); Nutrients (N, P, K, Ca, Mg) (N_content); Production costs (ProdCosts); Quadratic mean diameter (Dq); Recreation values (RecVal); Root biomass (RB); Shannon Index (ShInd); Site index (SInd); Species (Sp); Species distribution (Sp%); Standing timber value (StandingVal); Standing volumes (StandingVol); Stem bark biomass (StemBAB); Stem wood biomass (StemWB); Stocking (Stocking); Structure index (Struct); Thinned volume (ThinVol); Timber value (TimbVal); Top height (Ht); Total biomass (TB); Total volume (Tvol); Total yield (Tyield); Volume harvested on assortments (HTvolAssort); Volume under bark (VolUB); Volume under bark with stump (VolUB (stump)); Wages and salaries (W&S).

Table 5. Input data required for the DSS in each INTEGRAL case study area. Variables codes are specified in the abbreviation list and are ordered alphabetically.

CSA (Area)	Data Required at Landscape Level		Source Used to Provide the Information	Method to Approximate the Value
Bulgaria: TET (69,700 ha) YUN (4750 ha)	Site characteristics	Soil types	National Forest Inventory (NFI)	Data collection in the field
		Climate conditions	NFI	Phytosociology
	Stand characteristics	Sp: mean diameter and height, stand volume/ha, mean age, Sp%	NFI	Data collection in the field
	Management characteristics	Thinning regime + rotation length	Cadastre + Forest Management programs (FMP) + Forest Owners (FO typology)	Cadastre + expert definition of a % area per type
	Additional inputs	Climate evolution		
France: PON (101,000 ha)	Site characteristics	Site index for pine (Hdom 40)/100 for oak value (0–1)	Vegetation map derived from Modis (comparison from 2000 to 2014)	Empirical table: correspondence (vegetation type and Sind)
	Stand characteristics	Tree species and density. Age	IGN aerial photos	Expert + field validation
		Area	Cadastre with FO's ID number	
	Management characteristics	Thinning regime + rotation length + min #years between 2 thinning	FO typology + main stand type + Sind	Stratified random sampl. (forest size and fertility)
	Additional inputs	Prices per diameter classes	Public sale 'Office National des Forêts' (ONF) 2013	
Germany: MUN (60,000 ha) UPP (300,000 ha)	Site characteristics	Regional climate data (rainfall, vegetation period, temperature), soil characteristics (water + nutrient supply via indices)	Long term climate data + data from regional soil mappings	
	Stand characteristics	Tree species, Mean DBH/sp and/or layer, BA, Mean height	NFI	Data collection in the field: sample inventors for FM planning
	Management characteristics	Thinning regime	FMP + inventory strata characteristics	Expert definition of a % area per strata (NFI data)

Table 5. *Cont.*

CSA (Area)	Data Required at Landscape Level		Source Used to Provide the Information	Method to Approximate the Value
Ireland: NEW (187,820 ha) WES (1,060,000 ha)	Site characteristics	Upslope contributing area	Elevation SRTM DEM (90 m resolution)	
		Soil types	Teagasc Irish soil survey	
		Distance to water course	Geographic Information System techniques	
		Land use	Datasets recorded for statutory subsidies	
		Environmentally designated zone	Natura 2000 datasets and GIS techniques	
	Stand characteristics	Tree species	NFI	National Forest Information System (NFIS)
		Proportion of a tree species within a stand in percent		
		Productivity	NFI and productivity prediction model	NFIS and mathematical modelling from stand sampling
		Age	NFI	NFIS
	Management characteristics	Thinning regime are included in yield table selected	UK forest service	
Italy: ASI (103,000 ha) MOL (600 ha) ETN (25,300 ha)	Site characteristics	Productivity (m^3/ha/an)	Local FMPs	
	Stand Characteristics	Age class	Local FMPs	
		Vol/ha		
		Area		
	Management characteristics	Thinning regime	Local FMPs	

Table 5. *Cont.*

CSA (Area)	Data Required at Landscape Level		Source Used to Provide the Information	Method to Approximate the Value
Lithuania: SUV (66,000 ha) ZEM (37,900 ha)	Site characteristics	Soil types based on the slope, soil moisture and nutrient content	Standwise NFI + State Forest Cadastre	
	Stand Characteristics	Sp%, Age, H, D, Vol, BA by tree sp. and canopy layers and Area	Standwise NFI + State Forest Cadastre	Orthophotos + Data collection in the field
	Management characteristics	Ownership boundaries	Real estate register + State Forest Cadastre	Random sampl.(FO typology mapped prior simulations)
		Thinning regime + Final cuttings + Rotation length	Forest managers, FMP, State forest cadastre	Expert judgement
	Additional inputs	Costs and incomes from forestry activities	Economic statistics of local state forest enterprises, stakeholders	Experts' opinions
The Netherlands: SEV (8000 ha)	Site characteristics	Soil and digital elevation model characteristics	Dutch Soil map	
	Stand Characteristics	Age, biomass, stems per species per pixel	Detailed NFI (from 1981), projected to 2010 (checked spin-up run)	Extrapolation at pixel level
	Management characteristics	D or biomass target/sp per management area/regime	FMP from FS and municipalities and discussions with stakeholders	Experts' opinions
	Climate evolution characteristics	Monthly temperature and precipitation	Meteo from nearby station. For CC scenario KNMI: dutch Meteo station scenarios are used	Modelling
Slovakia: POD (21,255 ha) KYS (98,222 ha)	Site characteristics [39]	Bio-geo-climatic region	Map of Bio-ecological forest regions and sub-regions of Slovak Rep. incorporated in SIBYLA	
		Altitude, Slope, Aspect, Calendar year, Forest type	FMP database and FMP for forest stands in Slovak Republic, provided by the National Forest Centre (NFC)	Search of the desired characteristic in FMP database

Table 5. *Cont.*

CSA (Area)	Data Required at Landscape Level		Source Used to Provide the Information	Method to Approximate the Value
Slovakia: POD (21,255 ha) KYS (98,222 ha)	Stand Characteristics [39]	Representative species composition	FMP database and FMP for forest stands in Slovak Republic (NFC)	"Averaging" the information in FMP databases
		Site index		Carry out frequency analysis of the information in FMP databases
		Stand characteristics (Dmean, Hmean, stock vol/sp)		"Averaging" the information in FMP databases + transfer of desired information from Growth tables
	Management characteristics	Management zones	FMP database and FMP for forest stands in Slovak Republic (NFC)	Search for the desired characteristic in FMP database
		Area distribution of 10 year age classes		Summing the information from FMP and GIS cadastre databases
		Thinning regimes + Final cuttings + Rotation length	Forest managers, Silviculture experts and literature, FMP	Personal consultations + Literature review
	Climate evolution characteristics	Change of mean temperature and precipitation	IPCC report [40]	Modelling
Sweden: HEL (120,000 ha)	Site characteristics	Total and Productive Area, County Code, Altitude, Latitude, SInd, Soil Moisture Code, Vegetation Type	Stand register produced by combining NFI plot data and RSD	
	Stand Characteristics	SInd, Inventory Year, Mean Age, N/ha, BA, Sp%	Stand register produced by combining NFI plot data and RSD	
Sweden: VIL (850,000 ha)	Site characteristics	Mean site index of each strata	Site classification was based on site height indices (S_Hmean/age 100 yrs) per NFI's sp.	Interpolation
		Mean climatic condition of each strata	Mean of weather data from maps	Interpolation

Table 5. *Cont.*

CSA (Area)	Data Required at Landscape Level		Source Used to Provide the Information	Method to Approximate the Value
Sweden: VIL (850,000 ha)	Stand Characteristics	Mean composition in each strata	Mean of the stand composition given by NFI	Extrapolation from RSD and plot inventory
		Area of age classes of 10 years	Deduced from domestic growth and yield table	
		Spatial % of trees and dimensions (D, H, CL, CD, stem quality, damage)	Mean of the stand composition given by NFI	Extrapolation from RSD and plot inventory
	Management characteristics	Forest categories	Existing zones for protection/production	
		5 classes of management purposes traduced in thinning schedule	Expert assessment and cadastre	
		5 classes of naturalness based on species composition	NFI	
Portugal: CHA (74,600 ha) SOU (48,900 ha)	Site characteristics	SInd, altitude, climatic variables for each management unit (MU)	Cartography and meteorology Institutes	Models
	Stand Characteristics	MU area. Stand: sp, Struct, age, N/ha, Hdom and BA. Tree: DBH, H, SInd	NFI	Extrapolation from RSD and plot inventory
	Management characteristics	N/ha at planting, number of rotations, planning horizon, # shoots left per stump, age: first, last thinning, harvest and shoots selection, thinning: periodicity, type and intensity; annual list of silvicultural operations	Stakeholders	Experts' opinions + Literature review
	Additional inputs	Silvicultural operations' costs	Economic statistics	Literature review
Portugal: LEI (75,200 ha)	Site characteristics	Site index	Cartography and meteorology Institutes	Models
	Stand Characteristics	MU area, stand: Struct, sp, age, N/ha, Hdom and BA	NFI	Extrapolation from RSD and plot inventory
	Management characteristics	N/ha at planting, planning horizon, age: first, last thinning and harvest; thinning: periodicity, type and intensity	Stakeholders	Experts' opinions + Literature review
	Additional inputs	Silvicultural operations' costs	Economic statistics	Literature review

Basal area (BA); Crown diameter (CD); Crown length (CL); Diameter (D); Diameter at Breast Height (DBH); Dominant height (Hdom); Height (H); Mean diameter (Dmean); Mean height (Hmean); Number of trees per ha (N/ha); Site index (SInd); Species (Sp); Species distribution (Sp%); Structure index (Struct); Volume (Vol).

The DSS used for the case study can be classified according to the amount of input data they require (Figure 3). It should be noted that, the data required for one DSS may differ from case study to case study: for example, SIBYLA, used in Slovakia (case studies POD and KYS) and in Bulgaria (case studies TET and YUN) is not parametrised the same way in the two countries. Therefore, the required input data may also depend on the modelled area and the type of outputs partners needed for the project.

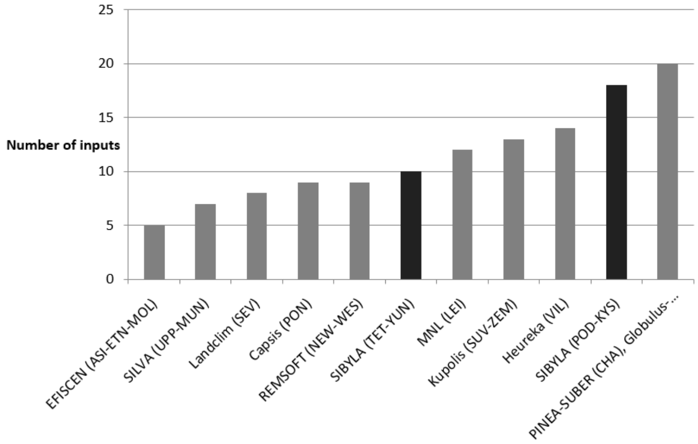

Figure 3. Number of inputs required per DSS for the different case study areas of the INTEGRAL project. The case studies using the same tool (SIBYLA) are shown in black. The last value represents the DSS used in Portugal: PINEA-SUBER (CHA), Globulus-PBIRROL-Pinaster-GYMMA (CHA-SOU), CASTANEA (SOU).

5.2. Sources of Input Data

In the case studies, the input data (Table 5) came from different sources and sometimes methods were used to validate it in the modelled area, mainly through checking values using measurements in the field (Table 3).

The stand characteristics needed for each DSS were mainly extracted from national forest inventories in all case studies and maps obtained from the extrapolation of remote sensing data. In one case (Capsis-PON in France), the data used to describe the stands did not comprise statistics from national inventory sampling plots, but a photointerpretation of the national forest inventory aerial photos carried out by the partners.

Climatic data were taken from forest inventory classifications, long-term series of satellite photos, nearby weather stations, maps of bio-ecological forest regions, and data from meteorological institutes.

The management characteristics are taken from cadastre information (when management type depends on property size), current local forest management plans or meetings with stakeholders.

5.3. Outputs Provided by the DSS for the Case Studies

The outputs provided by the DSS are shown in Table 6. Depending on the case study, the outputs mainly focused on wood production; however, for the INTEGRAL project, a number of outputs were produced to characterise the ecosystem services in each scenario. Certain case studies detailed wood production indicators; for example, in Bulgaria, four outputs out of eight were: harvested volume, standing volume, mortality volume and total biomass. In other regions, indicators were mainly developed for characterising various ecosystem services; for example, in Ireland, one output was the total harvested volume, while the other eight were tree carbon stock, water sedimentation risk, hen harrier habitat suitability, deer cover habitat, deer forage habitat, ground vegetation, nesting bird habitat, red squirrel habitat and human recreation.

Table 6. Outputs for the INTEGRAL case study areas by country and simulation period; provided directly by DSS or post-processing based.

Ecosystem Services Evaluated by Country (Simulation Period within INTEGRAL)	**Bulgaria (2014–2064)**	**France (2009–2069)**	**Germany (2012–2042)**	**Ireland (2012–2042)**	**Italy (2010–2040)**	**Lithuania (2013–2073) (2013–2043)**	**The Netherlands (2010–2100)**	**Sweden (2014–2044)**	**Slovakia (2014–2044)**	**Portugal (2014–2111)**
Ages						Sd				
Area of deciduous trees								Sd		
Average volume per tree		Sd								
Biomass	Sd								Sa [41]	
Costs, incomes and profits from forestry activities						Ld				
Deer cover habitat				Sd						
Deer forage habitat				Sd						
Discounted value of harvestable stock									Sa [42]	
Ecological stability									Ex	
Fire vulnerability		Sd					Sa			
Fuel wood									Sa [41]	
Ground vegetation				Sd						
Ground water protection			In						Sa [41]	
Harvested volume	Sd	Sd	Sa	Sd	Sd		Sd	Sd		Sd
Hen harrier habitat suitability				Sd						
Hunting income ratio in%									Ex	
Landscape amenity							Sa		Sa	
Leakage of dissolved organic carbon								Sd		
Leakage of methyl mercury								Sd		
MAI			Sa			Sd				
Mortality volume	Sd									
Mushrooms									Ex	
Natural dynamics (% area No-management)							Sa			

Table 6. *Cont.*

Ecosystem Services Evaluated by Country (Simulation Period within INTEGRAL)	Bulgaria (2014–2064)	France (2009–2069)	Germany (2012–2042)	Ireland (2012–2042)	Italy (2010–2040)	Lithuania (2013–2073) (2013–2043)	The Netherlands (2010–2100)	Sweden (2014–2044)	Slovakia (2014–2044)	Portugal (2014–2111)
Nesting birds habitat				Sd						
Potential to protect soil and water						In [43]				
Recreational value	In		In	Sd [44]	In	In				Sd
Red squirrel habitat				Sd						
Reindeer herding areas								Sd		
Relative stocking						Sd				
Saproxylic biodiversity		Sd			Sd			Sd		
Shannon diversity		In								
Total carbon content	Sd	Sd			Sd	Sd [45]	Sa	Sd		
Total carbon stock in trees			Sa	Sd						Sd
Total cork production										Sd [46]
Total biodiversity	Sd		In			Sd	Sa	Sd	Sa	
Total growing stock		Sd	Sa		Sd	Sd			Sa [41]	Sd
Total growing stock in mature stands						Sd		Sd		
Total harvested volume by diameter class						Sd				
Total pine nuts production										Sd [47]
Total standing value	Sd	Sd								
Total thinned volume										Sd
Total volume	Sd									
Tourism visitors									Ex	
Water sedimentation risk				Sd						
Wind vulnerability		Sd							Sa	

Text codes: Expert estimation [Ex]; Index [In]; Provided by DSS directly for each stand [Sd]; Provided by DSS directly for each strata [Sa]; Provided by DSS directly for the landscape [Ld]. Colours codes: Weighted sum by stand area (ha) 🟫; Weighted mean by stand area (ha) ▨; Weighted sum by strata area 🟦; Total sum of all stands 🟩; Total landscape value 🟧.

These two different case studies illustrate the diversity of outputs produced within the project. This variety is not only related to the DSS used, but also to the regional specificities and interests of the case studies. It can be observed that, even though the same tool (SIBYLA) was used for the Slovakian and the Bulgarian case studies, the outputs were different.

5.4. Relationship between Inputs and Outputs

As shown in Figure 4, the amount of output data (Table 6) provided by the tools for INTEGRAL is strongly related to the number of inputs (Table 5). A simple explanation for this is that in order to provide a wide range of information about a landscape, more complex modelling tools which need more input data are required. There is only a limited number of cases, such as SOU and CHA, in which landscape heterogeneity and the high number of models require many inputs for a limited number of outputs. Some of these outputs (listed in Table 6) were generated specifically for the project, and as they stand they do not fully represent the total outputs that the DSS are able to provide without carrying out additional work. However, this could mean that when choosing a landscape DSS based on growth models, the type and output number needed must be well-defined in order to pick the appropriate tool. In addition, the use of a more complex system which requires additional data and effort could be worthwhile as more landscape indicators are provided in the end. Nevertheless, this graph illustrates the need to develop more proxies on the landscape scale so that most of the values listed in Table 6 can be estimated for all landscapes.

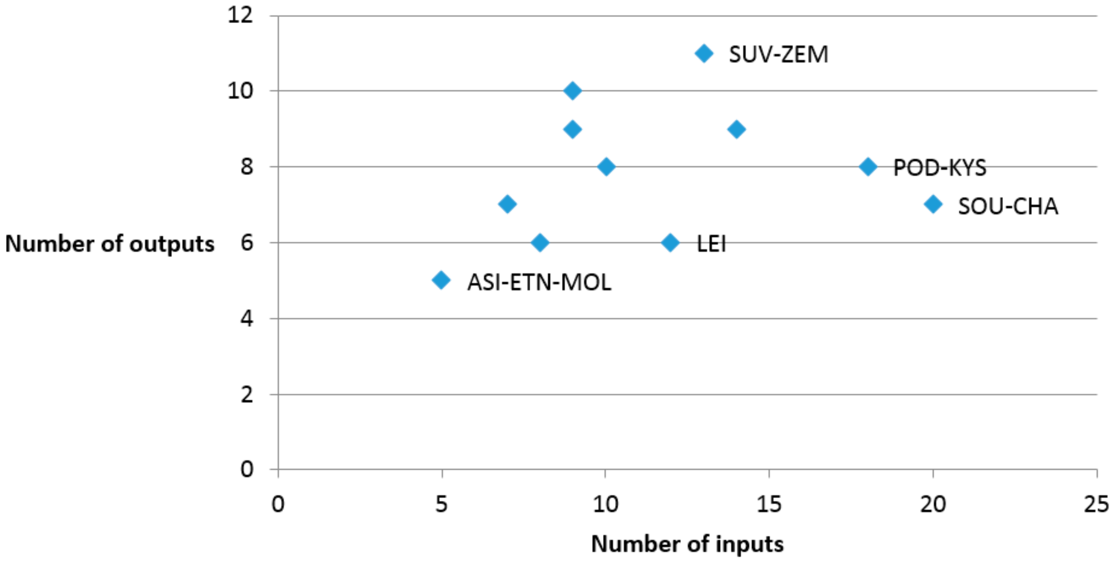

Figure 4. Number of outputs provided in the case studies for the INTEGRAL project depending on the number of inputs required to run the DSS used.

6. Discussion

6.1. Strengths and Weaknesses of the Listed Tools

The first limitation experienced in all the cases studies is the validity domain of the available tools. In a prospective study or when working on socioeconomic scenarios which comprise a broad set of possible futures such as in the INTEGRAL project [13] it is pertinent to work on forest landscape evolution under very diverse management options. As a consequence, in most cases it is necessary to foresee stand structure and associated services under extreme management options: short rotations, unusual thinning regimes (combination of biomass and timber products), unmanaged forest, tree species replacement, use of improved material, etc. Yield tables are obviously not adapted to address untested management. Empirical growth models often face the challenge of young ages modelling and extreme regime thinning, making their use problematic when running biomass management options. Process based growth models or hybrid models are often calibrated for a certain range of climatic conditions and their results should be interpreted with caution when reused outside their validity domain; however, they are expected to provide more reliable results if the climatic variables provided are trustworthy. The simulation of management options not always considered by growth models, such as unmanaged forests, assumes that the growth model can take complex parameters into account, including mortality (94% of INTEGRAL growth models), natural regeneration (10% of INTEGRAL growth models), mixed species (29% of INTEGRAL growth models) or trees species succession.

Almost all of the case studies in the INTEGRAL project have applied a regionally specific tool and growth model, and when this is not the case (e.g., SYBILLA, EFISCEN, LandClim), the parameterisation is regionally specific. There was very little exchange of growth and yield information between case studies. Especially in the light of climate change and regionally unknown management, one could consider the exchange of growth and yield information between regions to be better able to incorporate future situations in projections into the future. Moreover, our review revealed that most existing DSS are not able to manipulate information about climate and land use extensively, being limited to forest (i.e., NFI). Alternative workarounds could be found for all these cases, but assumptions underpinning these workarounds should be clearly explained to the end-user and identified from the beginning.

Figure 2 shows that there are many strategies to deal with the lack of data. Common sense assumes that the bigger and the more heterogeneous the forest landscape to be modelled, the more virtual stands you need to properly represent of the diversity of sites, tree species, stand structures and forest management. Each landscape simulation is a trade-off between the complexity of the situation, the outputs required and the data available to get a realistic result.

The fact that the Table 5 shows that some indicator for assessment of sustainable management at landscape level in some regions relied on the expert knowledge, shows that there is still a lack of relevant and validated indices that could be simulated in DSS for those specific items on large landscapes.

One important strength of the afore-described tools is that they can provide quantitative information which takes into account landscape characteristics and the heterogeneity of forest management over large areas. Some of the tools based on non-spatially explicit strata, offer a simple way to group homogenous plots or pixels in a realistic way and are probably the easiest to handle. Other more spatially explicit tools have the advantage of providing landscape indicator maps that are excellent for communication, but these can be misinterpreted if the underlying hypotheses are not well understood.

The different strategies on the sampling described in this paper are demonstrating that with a limited amount of input data, we can provide a good set of indicators adapted to regional issues (water quality, recreational value, mushrooms, etc.) on large landscapes for the three pillars of sustainability: ecology, economy, social. It also demonstrates that an additional effort in data collection is worthwhile as the number of outputs to assess sustainability increases with the amount of inputs. In addition, with the development of new dendrometric parameter acquisition tools, such as drones, satellites and LIDAR [48,49], the possibility of obtaining accurate data over large areas will increase. The combination of these stand data with digital elevation models, soils maps, and regional climate forecast [37] offer a promising avenue for landscape simulation tools. As input data becomes more reliable, the outputs will increase in accuracy and reliability for multiple uses and, more specifically, for resource assessment.

6.2. How Can the Appropriate Tool Be Selected to Run a Landscape Simulation in a Given Region?

The main criteria to consider before engaging in any forest landscape simulation are the existing forest status and the drivers that will be used to affect landscape evolution. Commonly, the main changes affecting a forest landscape are land use, management practices, hazards and climate. As also pointed out by Muys et al. [50], the main challenges for the current DSS rely on (i) simultaneously considering the ecosystem services trade-offs; (ii) balancing forest management options with the implications of local climate and land use changes (afforestation and deforestation); and (iii) including the local communities' needs and stakeholders' expectations (i.e., social science component) while simulating management effects on forest stand (or landscape) development. In particular, Pastorella et al. [51] highlighted that stakeholders perceive DSS as inadequate to differentiate the stakeholders' perceptions and needs, but INTEGRAL project tackled this challenge.

The INTEGRAL project demonstrates that in most European regions, it is possible to find growth models [15] and landscape DSS [52] matching the on-site species and that workaround options exists, although they may affect the accuracy of the results, requiring their cautious interpretation. When simulation includes the replacement of on-site species by a very new species (Table 2 vs. Table 3), it is extremely risky to use models without carrying out field trials to calibrate the site indices. This is true for most of the species replacement strategies.

An increasing interest in landscape simulation relates to conversion of forest to biomass [53]. The INTEGRAL results show that a very limited number of models are currently able to take short rotations and biomass production into account; this is an issue that must be considered before making any choices.

As climate was not a variable taken into account in the INTEGRAL European case studies, a limited number of growth models used (37% in INTEGRAL) can account for climate change uncertainty; according to the ForestDSS Community of Practice (ForestDSS.org) [52,54] inventory only 19% of existing DSS can. This issue will become increasingly important in the future and could become a key criterion when selecting a landscape simulation for running forecasts over decades.

Data availability is an important criterion, and DSS providing a large set of outputs with a limited number of input data will always be preferred. A challenge for simulation is to design a tool in which there is a compromise between accuracy, relevance of the results, and input data collection work.

Output parameters should be clearly targeted before choosing a tool; a complex model requiring huge input data compilation efforts is not necessary, if the expected result is only growing stock. Output parameters, and the way they are built (see reference in Table 5), are of course very important, as they comprise the way in which simulated landscapes sustainability will be compared. As demonstrated in this paper, in most cases timber production and dendrometric data are well described. Particular attention should be given to the other indicators (Table 6) that are derived from these values, in order to assess sustainability on the landscape level: biodiversity [5], vulnerability, standing value, recreational index [44], carbon storage, etc.

To increase the effectiveness of sustainable forest management through the use of decision support tools, the standardization of data and approaches would be needed. For example, the inclusion of criteria and indicators for sustainable forest management as available at EU scale may improve the evaluation of the implications of decision support tools on forest functionality towards a standardized way. Some proposals come from Santopuoli et al. [55] for social and cultural sustainability, and by Pereira et al. [56] for biodiversity conservation. However, the different representation of the forest landscape in the different DSS makes adoption of landscape level post-calculation indicators applied in other regions or DSS difficult.

7. Conclusions

In conclusion, the main findings from the implementation of the DSS within the INTEGRAL project in European forest landscapes denote that: (i) there is a large diversity of tools which run landscape simulation; (ii) whatever tools is selected it is possible to consider local ecological and socio-economic conditions; (iii) landscape dynamics as a consequence of external disturbance still need to be included (i.e., land use change and climate); and (iv) comparison between case studies is rather difficult due to poor standardisation of adopted data and approaches. Taking these issues into account, the end-user needs a user-friendly [57] decision support tool which will run forest landscape simulation and make the most of existing (online) information (NFI, soil maps, past and future climate, etc.) and use data automatically collected from drones or remote sensing data. In consequence, the user will be able to focus on the definition of forest management depending on end-user expectations and output analysis, instead of focusing on site characteristics at the initial stages.

The INTEGRAL project also highlighted the high impact of forest management decisions on forest ecosystem services linked to local communities for different landscapes in Europe. To assess this impact using decision support tools, process-based and agent-based approaches should be combined in order to detect and compare peculiarities and differences between European forest landscapes or socio-economic scenarios. Accordingly, from decision-making to the operational level, the sustainability in forest landscapes may be enhanced through simultaneously considering the local communities' needs and the resilience and vulnerability of forest ecosystems to increasing stresses and anthropogenic pressures. It is therefore necessary to develop a good understanding of forest owner choices and to validate robust indicators able to assess forest sustainability and vulnerability throughout very large areas from these new datasets and the existing growth models. Improving and enhancing the valorisation of forest management as a driver of local development should be the mandate for developing the future-oriented decision support tools.

Finally, in order to make current decision support tools more flexible in consideration of forest management options, sustainability indicators and spatial interactions would be expected to consider ecosystem dynamics and driving forces (e.g., sustainable development policies) in a more integrated way.

Acknowledgments: The INTEGRAL project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No. 282887. http://www.integral-project.eu/. Moreover, financial support by the Transnational Access to Research Infrastructures activity in the 7th Framework Programme of the EC under the Trees4Future project (No. 284181) for conducting the research is gratefully acknowledged. This research has also received funding from the European Union H2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 691149 (SuFoRun). Researcher Jordi Garcia-Gonzalo was supported by a "Ramon y Cajal" research contract from the MINECO (Ref. RYC-2013-14262) and has received funding from CERCA Programme/Generalitat de Catalunya. This paper could be achieved thanks to support of EFIATLANTIC donors: Conseil regional d'Aquitaine, Ministère de l'agriculture et de la forêt.

Author Contributions: Authors who carried out literature review and text editing: Christophe Orazio, Rebeca Cordero Montoya., Margot Régolini, Geerten Hengeveld, Matteo Vizzarri. All authors provided information on models and contributed to table design, ran landscape DSS in regional case studies.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

CC	Climate Change
CO_2	Carbon dioxide
DEM	Digital Elevation Model
FMA	Forest Management Action
FMP	Forest Management Plan
FO	Forest Owner
FS	Forest Service
IGN	Institut national de l'information géographique et forestière
IPCC	The Intergovernmental Panel on Climate Change
KNMI	The Royal Netherlands Meteorological Institute
MAI	Mean Annual Increment
NFC	National Forest Centre
NFI	National Forest Inventory
NFIS	National Forest Information System
NO_x	Nitrogen oxide
ONF	Office National des Forêts
RSD	Remote Sensing Data
SRTM	Shuttle Radar Topographic Mission

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