Some Iron(III) Catalyzed Michael Reactions of Chiral Donors, bis-Donors, and a bis-Acceptor

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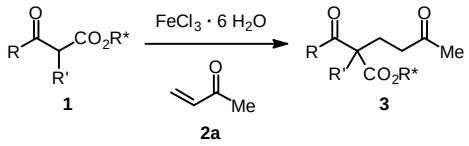
Abstract. Michael reactions of β-keto esters **1a**–**1h** with methyl vinyl ketone (**2a**) catalyzed by $FeCl_3 \cdot 6\ H_2O$ (5 mol%) proceed with up to 99% yield. Conversion of β-keto esters **1a**–**1e** derived from chiral alcohols with **2a** result in only very low diastereoselectivities (max. *de* 20%). A bis-β-keto ester **1i** and a bis-vinyl ketone **2b** – both valuable monomers for poly-Michael reactions – are synthesized from common starting materials in up to gram quantities.

The conjugate, base catalyzed addition of a β-dicarbonyl compound to an acceptor activated olefin is one of the most important C–C bond forming reactions in organic synthesis [1]. Being generally a high yielding and very efficient process, in some cases a number of side- and subsequent reactions, such as ester solvolysis, aldol-cyclizations, and retro-Claisen-type decompositions, result in a low chemoselectivity of the classic base catalyzed Michael reaction. To overcome these drawbacks Brönstedt basic reaction conditions have to be avoided, and a number of neutral metal compounds have been reported as catalysts in the past years [2]. Iron(III)chloride hexahydrate has been introduced by us being one of the most efficient metal catalysts for a Michael reaction of a β-keto ester **1** with vinyl ketones **2** (Scheme 1) [3]. $FeCl_3 \cdot 6\ H_2O$ is a non-toxic, very cheap and insensitive material. Recently, we reported on the first poly-Michael reaction of a bis-donor with a bis-acceptor catalyzed by $FeCl_3 \cdot 6\ H_2O$ [4]. Herein, we wish to report on the synthesis of the respective starting materials **1i** and **2b** as well as their conversion in model Michael reactions. Moreover, since most of the Michael products **3** bear at least one stereogenic center, the control of stereochemistry is an important issue [5]. Besides the use of chiral catalysts for asymmetric Michael reactions [6] the application of chiral auxiliaries is a reasonable strategy which has been investigated continuously [7]. One of our approaches to address this problem applies the use of oxo esters being esterified with chiral alcohols such as phenylethanol, menthol, and borneol. To have a flexible access to these materials we have established a very simple protocol for transesterifications based on the azeotropic removal of methanol with cyclohexane from a reaction mixture [8]. Herein, we report on our results in Fe(III) catalyzed conversions of these chiral β-keto esters with methyl vinyl ketone (MVK, **2a**).



Scheme 1 Iron(III) catalyzed Michael reactions of β-keto esters **1** with MVK (**2a**).

Results and Discussion

Michael Reactions

A number of β-keto esters **1** resulting from azeotropic transesterifications [8] of the corresponding methyl esters with *rac*-phenyl ethanol (**1a**, **1c**, and **1f**), (1*R*,3*R*,4*S*)-(–)-menthol (**1b** and **1e**) as well as (1*S*,2*R*)-(–)-*endo*-borneol (yielding **1d**) were converted with 1.2 eq MVK (**2a**) and 5 mol% $FeCl_3 \cdot 6\ H_2O$ at ambient temperature in CH_2Cl_2. Products **3a**–**3f** were obtained after chromatography in good to excellent yields (Scheme 2). With respect to stereoselectivity diastereoisomers were always obtained in about 1 : 1 ratio (best value 60 : 40 for **3a**). Consequently, chiral alcohols do not seem to be suitable auxiliaries to convert derived β-keto esters in Fe(III) catalyzed Michael reactions. Analogously, products **3g** and **3h** were obtained from the corresponding six- and seven-membered isobutyl esters **1g** and **1h**. Compounds **3g** and **3h** are required as racemic reference materials in our project on the asymmetric catalysis of Michael

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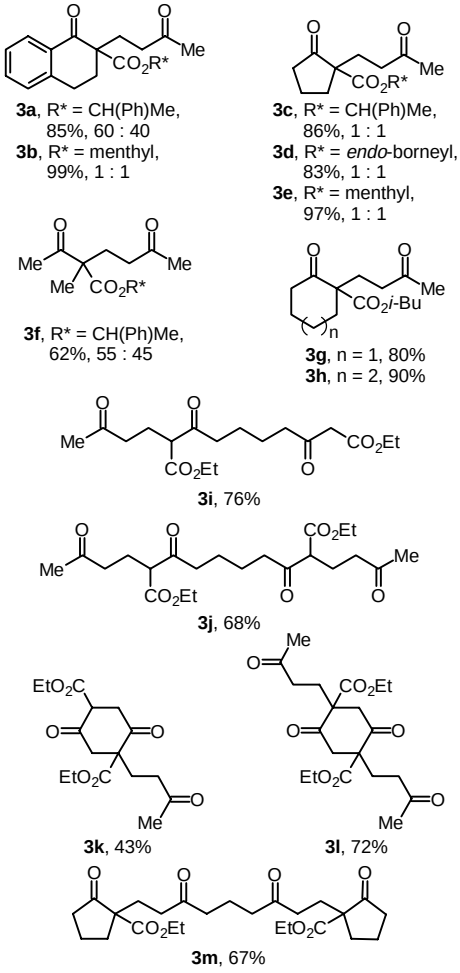
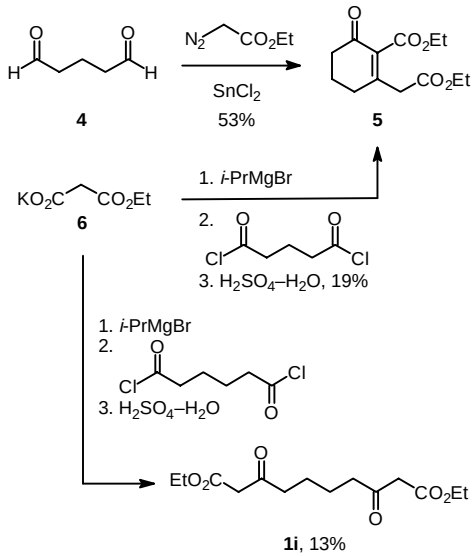
reactions [6e, 6f]. Bis-donors **1i** (Scheme 3) and **1k** (diethyl 2,5-cyclohexanedione 1,4-dicarboxylate) [9] were converted with MVK (**2a**) under more diluted conditions as applied for the preparation of polymeric materials [4]. Mono-adduct **3i** was obtained by application of 1 eq MVK (**2a**). The yield was moderate due to the formation of the bis-adduct as a by-product. Formation of the mono-adduct **3k** required 4 eq MVK (**2a**) resulting in a moderate yield at ambient temperature. Bis-adduct **3j** was obtained at 23 °C applying 4 eq MVK (**2a**). Having quantitative conversion (by TLC) the low yield was presumably due to a number of unspecified condensation side processes of the very polar material. Bis-donor **1k** did not form any bis-adduct **3l** at ambient temperature. Elevated temperature and 4 eq MVK (**2a**) were required in this case. Consequently, bis-donor **1k** is less suitable for any polyaddition reaction. Bis-acceptor **2b** (Scheme 4) was reacted with 5 eq of ethyl 2-oxocyclopentane carboxylate (**1m**) to yield 67% of the bis-adduct **3m** at 23 °C. In this case the relatively low yield might be due to the sensitivity as well as to the high volatility of starting material **2b**.



Scheme 2 Products of Fe(III) catalyzed Michael reactions of donors **1a**–**1i** and **1k** with MVK (**2a**) and donor **1m** with bis-acceptor **2b**. Yields and ratios of diastereoisomers (for **3a**–**3f**).

Synthesis of the bis-donor

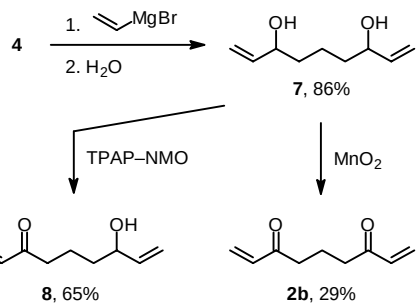
To access a material being a suitable bis-Michael donor we first considered double tin-mediated conversion of glutaric aldehyde (**4**) with ethyl diazoacetate known as an established method for β-keto ester formation [10]. However, under reaction conditions six-membered ring formation by subsequent intramolecular condensation seemed to be a very favorable process, since compound **5** [11] was the only isolable product out of this reaction. Thus, we decided to rely on another protocol which was reported in the literature to successfully yield a dialkyl 3,7-dioxononanedioate [12]. But conversion of doubly deprotonated monoethyl malonate (**6**) with glutaroyl chloride (followed by protonation and decarboxylation) again yielded the cyclic product **5** as the only unique material. Consequently, we thought that seven-membered ring formation might be a less favorable subsequent process. And indeed, analogous conversion of **6** with adipoyl chloride yielded compound **1i**, however, in low yield.



Scheme 3 Synthesis of the bis-donor **1i**.

Synthesis of the bis-acceptor

Synthesis of the bis-acceptor **2b** started from dialcohol **7** being readily available by conversion of glutaric aldehyde (**4**) with vinyl Grignard reagent [13]. The generally very reliable TPAP–NMO method [14] applied to substrate **7** yielded only the mono-oxidized product **8**. Double oxidation was achieved with MnO_2 [15] furnishing compound **2b**. The low yield originates from the high volatility of product **2b** [16].



Scheme 4 Synthesis of the bis-acceptor **2b**

Conclusion

A number of Fe(III) catalyzed Michael reactions of β-keto esters with vinyl ketones were reported. The yields range from moderate to excellent. In case of the conversion of esters derived from chiral alcohols very low or no stereoinduction was obtained. The syntheses of a bis-β-keto ester as well as a bis-vinyl ketone were performed in moderate yields. However, up to gram quantities can be obtained, since the starting materials are readily available.

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Experimental

All manipulations involving Grignard reagents were carried out in flame dried glassware under an atmosphere of argon and with absolute THF, which was freshly distilled from potassium. Absolute MeCN was purchased as HPLC grade quality and dried over molecular sieves (4 Å). Absolute CH_2Cl_2 was purchased from Fluka. Column chromatography was accomplished with Merck silica gel (type 60, 0.063–0.200 mm) using *tert*-butyl methyl ether (MTB) and petroleum ether (*b.p.* 40–60 °C) (PE). Donors **1a**–**1f** were prepared as recently published [8]. Transesterifications with low boiling alcohols to yield **1g** and **1h** were performed as previously reported [6e]. Compound **1k** was prepared according to a literature protocol [9]. All other starting materials were commercially available. All reagents were used as purchased, except glutaric dialdehyde, which was extracted from a NaCl-saturated 50% aqueous solution and always freshly distilled prior to use. Vinyl magnesium chloride was purchased from the Aldrich Chemical Co. – ^{1}H NMR: Bruker AM 400 (400 MHz) and AC 200 (200 MHz). – ^{13}C NMR: Bruker AC 200 (50 MHz). – ^{13}C resonances were assigned by DEPT experiments. – MS: Varian MAT 711 and MAT 955Q (high resolution). – IR: Nicolet Magna IR 750. – Elemental analyses: Analytik Jena Vario EL. – Optical rotations: Perkin Elmer polarimeter 341.

rac-1-Phenylethyl 2-methyl-3-oxobutanoate (**1f**) [17]

Preparation from methyl 2-methyl-3-oxobutanoate and *rac*-1-phenylethanol followed a published procedure [8]. – R_f (SiO_2, PE/MTB 1 : 1) = 0.54. – ^{1}H NMR (200 MHz, $CDCl_3$): two diastereoisomers, ratio 1 : 1, partly doubled signal set, δ/ppm = 1.34 (d, J = 7.2 Hz, 3H), 1.35 (d, J = 7.2 Hz, 3H), 1.54 (d, J = 6.5 Hz, 3H), 1.55 (d, J = 6.7 Hz, 3H), 2.07 (s, 3H), 2.21 (s, 3H), 3.50 (q, J = 7.1 Hz, 2H), 5.92 (q, J = 6.6 Hz, 2H), 7.28–7.36 (m, 10H). – ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$): two diastereoisomers, partly doubled signal set, δ/ppm = 12.52 (CH_3), 12.56 (CH_3), 21.83 (CH_3), 21.89 (CH_3), 28.18 (CH_3), 28.37 (CH_3), 53.69 (CH), 53.79 (CH), 73.32 (CH), 125.99 (CH), 128.02 (CH), 128.48 (CH), 140.84 (C), 140.90 (C), 169.64 (C), 203.29 (C), 203.40 (C). – MS (EI, 70 eV), *m/z* (%): 220 (1) [M^+], 192 (6), 121 (58), 105 (100). – IR (ATR): ν_{max}/cm^{-1} = 2984 (m), 2940 (m), 1739 (vs), 1714 (vs), 1453 (m), 1358 (m), 1242 (m), 1200 (s), 1154 (s), 1096 (m), 1062 (s), 1029 (m), 995 (m), 762 (m), 699 (s). – $C_{13}H_{16}O_3$ (220.27): Mol. mass calcd. 220.1099, found 220.1105 (HRMS).

Isobutyl 2-oxocyclohexanecarboxylate (**1g**)

Preparation from ethyl 2-oxocyclohexanecarboxylate and isobutanol followed a published procedure [6e]. – ^{1}H NMR (200 MHz, $CDCl_3$): enol/keto-tautomer 9 : 1, enol-tautomer: δ/ppm = 0.93 (d, J = 6.8 Hz, 6H), 1.52–1.72 (m, 4H), 1.88–2.06 (m, 1H), 2.16–2.30 (m, 4H), 3.91 (d, J = 6.7 Hz, 2H), 12.21 (s, 1H). – ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$), enol-tautomer: δ/ppm = 18.86 (CH_3), 21.74 (CH_2), 22.18 (CH_2), 22.22 (CH_2), 27.58 (CH), 28.87 (CH_2), 69.91 (CH_2), 97.54 (C), 171.78 (C), 172.51 (C). – MS (EI, 70 eV); *m/z* (%): 198 (82) [M^+], 170 (25) [M^+ – CO], 142 (62) [M^+ – $Me_2C{=}CH_2$], 125 (100) [M^+ – *i*Bu]. – IR (ATR): ν_{max}/cm^{-1} = 2939 (s), 2874 (m), 1744 (s), 1716 (s), 1654 (vs), 1615 (s), 1403 (s), 1359 (s), 1295 (s), 1259 (s), 1218 (vs), 1175 (s), 1081 (s), 985 (m), 831 (s). – $C_{11}H_{18}O_3$ (198.26): Mol. mass calcd. 198.1256, found 198.1249 (HRMS).

Isobutyl 2-oxocycloheptanecarboxylate (**1h**)

Preparation from methyl 2-oxocycloheptanecarboxylate and isobutanol followed a published procedure [6e]. – ^{1}H NMR (200 MHz, $CDCl_3$) keto/enol-tautomer 8 : 2: δ/ppm = 0.88 (d, J = 6.6 Hz, 3H), 0.92 (d, J = 6.5 Hz, 3H), 1.35–2.18 (m, 9H), 2.32–2.45 (m, 1H), 2.53–2.63 (m, 1H), 3.51 (dd, J = 10.0 Hz, J = 4.0 Hz, 1H), 3.80–3.96 (m, 2H), 12.71 (s, 0.2 × 1H; enol-OH). – ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$), keto-tautomer: δ/ppm = 18.96 (CH_3), 24.42 (CH_2), 27.59 (CH_2), 27.62 (CH), 27.87 (CH_2), 29.65 (CH_2), 43.00 (CH_2), 58.99 (CH), 71.06 (CH_2), 170.52 (C=O), 208.90 (C=O); enol-tautomer: δ/ppm = 19.04 (CH_3), 24.30 (CH_2), 24.57 (CH_2), 27.29 (CH_2), 27.70 (CH), 31.94 (CH_2), 35.27 (CH_2), 70.29 (CH_2), 101.64 (C), 172.99 (C), 179.44 (C). – MS (EI, 70 eV); *m/z* (%): 212 (12) [M^+], 184 (10) [M^+ – CO], 156 (26) [M^+ – $Me_2C{=}CH_2$], 138 (100) [M^+ – H_2O – $Me_2C{=}CH_2$]. – IR (ATR): ν_{max}/cm^{-1} = 2960 (m), 2932 (s), 1742 (vs), 1707 (vs), 1639 (m), 1612 (m), 1455 (m), 1312 (m), 1241 (s), 1215 (s), 1192 (s), 1156 (m), 1125 (m), 1003 (m). – Mol. mass calcd. 212.1412, found 212.1410 (HRMS).

$C_{12}H_{20}O_3$	Calcd.:	C 67.89	H 9.50
(212.29)	Found:	C 67.61	H 9.61.

Diethyl 3,8-dioxodecanedioate (**1i**)

A Grignard solution prepared from activated Mg turnings (1.00 g, 420 mmol) and isopropylbromide (3.7 ml, 4.9 g, 39 mmol) in THF (50 ml) at 70 °C (1 h) was diluted with THF (160 ml), and potassium monoethyl malonate (**6**) (6.8 g, 39 mmol) was added at ambient temperature. The resulting suspension was heated to 70 °C for 2 h, adipoyl dichloride (2.9 ml, 3.7 g, 20 mmol) was added and the mixture stirred over night at room temperature. After addition of diluted H_2SO_4 (60 ml H_2O, 6.0 mol conc. H_2SO_4) the aqueous layer was extracted three times with MTB. The combined organic layers were washed with $NaHCO_3$ (200 ml saturated aqueous solution) and brine (100 ml) and dried over $MgSO_4$. After filtration and evaporation of the solvent, chromatography on SiO_2 (PE/MTB 1 : 1, R_f = 0.17) yielded the bis-donor **1i** (0.76 g , 2.7 mmol, 13%) as a colourless oil. – ^{1}H NMR (400 MHz, $CDCl_3$): δ/ppm = 1.27 (t, J = 7 Hz, 6H), 1.57–1.62 (m, 4H), 2.53–2.59 (m, 4H), 3.42 (s, 4H), 4.19 (q, J = 7 Hz, 4 H). – ^{13}C{^{1}H} NMR (50 MHz ,$CDCl_3$): δ/ppm = 14.04 (CH_3), 22.56 (CH_2), 42.55 (CH_2), 49.22 (CH_2), 61.33 (CH_2), 167.13 (C=O), 202.37 (C=O). – MS (EI, 70 eV); *m/z* (%): 287 (8) [M + H$^+$], 269 (62) [M$^+$ – OH], 241 (34) [M$^+$ – EtO], 223 (100), 195 (38), 153 (60), 125 (25), 111 (34). – IR (ATR): ν_{max}/cm^{-1} = 2983 (m), 2940 (m), 1742 (vs), 1715 (vs), 1411 (m), 1368 (m), 1316 (s), 1242 (s), 1181 (m), 1095 (m), 1028 (s). – Mol mass. calcd. 287.1495 ($C_{14}H_{23}O_6$); found 287.1495 (M + H$^+$, HRMS).

$C_{14}H_{22}O_6$	Calcd.: C 58.73	H 7.74
(286.32)	Found: C 58.61	H 7.82.

3,7-Dioxo-1,8-nonadiene (**2b**)

A solution of bis-allylic alcohol **7** (*vide infra*) (2.00 g, 12.8 mmol) in abs. CH_2Cl_2 (20 ml) was added dropwise at ambient temperature to a suspension of MnO_2 (10.0 g, 115 mmol) in abs. CH_2Cl_2 (300 ml). The conversion was monitored by TLC, and 1 g-portions of MnO_2 were added every 30 min (about ten times) until no starting material was detectable any more. The resulting suspension was filtered through a glass frit (CH_2Cl_2), the filtrate was evaporated and the residue chromatographed on SiO_2 (pentane/Et_2O 1 : 1, R_f = 0.28) to yield the bis-acceptor **2b** (566 mg, 3.72 mmol, 29%) as a colourless volatile liquid. – ^{1}H NMR (400 MHz, $CDCl_3$): δ/ppm = 1.95 (pentet, J = 7.0 Hz, 2H), 2.66 (t, J = 7.0 Hz, 4H), 5.83 (dd, J = 1.1 Hz, J = 10.3 Hz, 2H), 6.23 (dd, J = 1.2 Hz, J = 17.0 Hz, 2H), 6.34 (dd, J = 10.3 Hz, J = 17.1 Hz, 2H). – ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$): δ/ppm = 17.90 (CH_2), 38.31 (CH_2), 128.26 (CH_2), 136.41 (CH), 200.23 (C=O). – MS (EI, 70 eV); *m/z* (%): 152 (1) [M$^+$], 125 (1) [M$^+$ – C_2H_3], 124 (3) [M$^+$ – C_2H_4], 109 (3), 97 (16) [M$^+$ – COCH=CH_2], 96 (10), 83 (11), 82 (6), 70 (7), 55 (100). – IR (ATR): ν_{max}/cm^{-1} = 2941 (m), 1721 (s), 1699 (vs), 1678 (vs), 1615 (s), 1446 (m), 1402 (vs), 1373 (m), 1314 (m), 1283 (m), 1253 (m), 1202 (s), 1181 (s), 1100 (s), 1066 (m), 1032 (m), 987 (vs), 966 (vs), 928 (m), 885 (m). – $C_9H_{12}O_2$ (152.19): – Mol. mass calcd. 152.0837, found 152.0851 (HRMS).

Iron(III) Catalyzed Michael Reaction (General Procedure)

A mixture of oxo ester **1** (1.0 eq), MVK (**2a**) (1.2 eq) and $FeCl_3 \cdot 6\ H_2O$ (0.05 eq) in CH_2Cl_2 (0.1 ml/mmol oxo ester) was stirred at room temp. over night. The mixture was directly chromatographed on SiO_2 (PE/MTB) to give the Michael reaction product.

rac-1-Phenylethyl 2-(3-oxobutyl)-1-tetralone-2-carboxylate (**3a**)

Following the general procedure the *rac*-1-phenylethyl ester **1a** (136 mg, 0.460 mmol), MVK (40 mg, 0.55 mmol) and $FeCl_3 \cdot 6\ H_2O$ (6.0 mg, 0.023 mmol) in CH_2Cl_2 (0.2 ml) yielded the product **3a** (143 mg, 0.392 mmol, 85%) after chromatography (PE/MTB 5 : 1, R_f = 0.07) as a colourless oil. – ^{1}H NMR (200 MHz, $CDCl_3$): two diastereoisomers, ratio 58 : 42, partly doubled signal set; δ/ppm = 1.34 (d, J = 6.6 Hz, 0.42 × 3H), 1.44 (d, J = 6.6 Hz, 0.58 × 3H), 1.96–2.22 (m, 2H), 2.01 (s, 0.42 × 3H), 2.07 (s, 0.58 × 3H), 2.25–2.62 (m, 3H), 2.65–2.85 (m, 2H), 2.88–2.98 (m, 1H), 5.84 (q, J = 6.6 Hz, 1H), 6.94–6.98 (m, 1H), 7.09–7.18 (m, 3H), 7.20–7.33 (m, 3H), 7.44 (tt, J = 7.5 Hz, J = 1.8 Hz, 1H), 8.02 (dt, J = 7.8 Hz, J = 1.6 Hz, 1H). – ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$): two diastereoisomers, partly doubled signal set; δ/ppm = 21.77 (CH_3), 21.86 (CH_3), 25.62 (CH_2), 27.59 (CH_2), 29.67 (CH_3), 29.67 (CH_3), 31.61 (CH_2), 31.81 (CH_2), 38.85 (CH_2), 56.24 (C), 73.28 (CH), 125.50 (CH), 125.77 (CH), 126.61 (CH), 127.55 (CH), 127.59 (CH), 127.62 (CH), 127.82 (CH), 128.15 (CH), 128.31 (CH), 128.53 (CH), 128.62 (CH), 132.09 (C), 132.16 (C), 133.23 (CH), 133.28 (CH), 140.77 (C), 140.84 (C), 142.46 (C), 142.53 (C), 170.77 (C), 170.86 (C), 195.23 (C), 195.38 (C), 207.46 (C), 207.50 (C). – MS (EI, 70 eV); *m/z* (%): 365 (1) [M + H$^+$], 261 (100), 243 (19), 199 (14), 191 (19), 105 (24). – IR (ATR): ν_{max}/cm^{-1} = 2932 (m), 1717 (vs), 1687 (vs), 1601 (s), 1453 (s), 1372 (m), 1354 (m), 1284 (m), 1235 (s), 1222 (s), 1193 (s), 1171 (s), 1093 (m), 1060 (s), 1028 (m), 993 (m), 928 (m), 761 (m), 741 (s), 699 (s). – Mol. mass calcd. 365.1753 ($C_{23}H_{25}O_4$), found 365.1755 (M + H$^+$, HRMS).

$C_{23}H_{24}O_4$	Calcd.: C 75.80	H 6.64
(364.44)	Found: C 75.60	H 6.70.

(1R,3R,4S)-(–)-Menthyl 2-(3-oxobutyl)-1-tetralone-2-carboxylate (**3b**)

Following the general procedure the (1*R*,3*R*,4*S*)-(–)-menthyl ester **1b** (414 mg, 1.26 mmol), MVK (132 mg, 1.89 mmol) and $FeCl_3 \cdot 6\ H_2O$ (17 mg, 0.063 mmol) in CH_2Cl_2 (0.5 ml) yielded the product **3b** (500 mg, 1.25 mmol, 99%) after chromatography (PE/MTB 5 : 1, R_f = 0.14) as a colourless oil. – $[\alpha]_D^{23}$ = –34 (c = 4.0 g/l, $CHCl_3$). – ^{1}H NMR (200 MHz, $CDCl_3$): two diastereoisomers, ratio 1 : 1, partly doubled signal set; δ/ppm = 0.38 (d, J = 6.9 Hz, 3H), 0.49 (d, J = 6.9 Hz, 3H), 0.61–0.98 (m, 6H), 0.69 (d, J = 7.0 Hz, 3H), 0.78 (d, J = 6.8 Hz, 3H), 0.80 (d, J = 7.0 Hz, 3H), 0.83 (d, J = 6.5 Hz, 3H), 1.16–2.20 (m, 20H), 2.08 (s, 3H), 2.10 (s, 3H), 2.40–2.53 (m, 4H), 2.65–2.79 (m, 2H), 2.91–2.98 (m, 2H), 4.55 (qt, J = 10.8 Hz, J = 4.3 Hz, 1H), 4.60 (dt, J = 10.9 Hz, J = 4.3 Hz, 1H), 7.11–7.29 (m, 4H), 7.38 (dt, J = 7.5 Hz, J = 1.8 Hz, 1H), 7.40 (dt, J = 7.5 Hz, J = 1.7 Hz, 1H), 7.92 (dd, J = 7.8 Hz, J = 1.3 Hz, 1H), 7.95 (dd, J = 7.8 Hz, J = 1.3 Hz, 1H). – ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$): δ/ppm = 15.05 (CH_3), 15.71 (CH_3), 20.52 (CH_3), 20.62 (CH_3), 21.74 (CH_3), 21.79 (CH_3), 22.36 (CH_2), 22.78 (CH_2), 25.06 (CH), 25.71 (CH_2), 25.84 (CH_2), 27.52 (CH_2), 27.97 (CH_2), 29.73 (CH_3), 31.10 (CH), 31.19

(CH), 31.69 (CH_2), 31.82 (CH_2), 33.86 (CH_2), 38.97 (CH_2), 39.08 (CH_2), 40.13 (CH_2), 40.17 (CH_2), 46.32 (CH), 46.48 (CH), 56.31 (C), 56.31 (C), 75.52 (CH), 126.52 (CH), 126.59 (CH), 127.51 (CH), 127.58 (CH), 128.46 (CH), 128.51 (CH), 132.16 (C), 132.40 (C), 133.17 (CH), 133.21 (CH), 142.41 (C), 142.45 (C), 171.04 (C), 171.36 (C), 195.41 (C), 207.52 (C), 207.56 (C). – MS (EI, 70 eV); *m/z* (%): 389 (2) [M^+], 328 (7), 260 (44), 242 (8), 190 (100), 172 (17), 157 (13). – IR (ATR): ν_{max}/cm^{-1} = 2955 (vs), 2929 (s), 2870 (m), 1720 (vs), 1690 (s), 1601 (m), 1454 (m), 1370 (m), 1355 (m), 1285 (m), 1241 (s), 1222 (s), 1196 (s), 1179 (s), 1094 (m), 1038 (m), 982 (m), 963 (m), 914 (m), 741 (s). – Mol. mass calcd. 398.2457, found 398.2457 (HRMS).

$C_{25}H_{34}O_4$	Calcd.: C 75.34	H 8.60
(398.54)	Found: C 75.38	H 8.59.

rac-1-Phenylethyl 2-oxo-1-(3-oxobutyl)cyclopentanecarboxylate (**3c**)

Following the general procedure *rac*-1-phenylethyl ester **1c** (784 mg, 3.38 mmol), MVK (260 mg, 3.71 mmol) and $FeCl_3 \cdot 6\ H_2O$ (46 mg, 0.17 mmol) in CH_2Cl_2 (0.5 ml) yielded the product **3c** (882 mg, 2.92 mmol, 86%) after chromatography (PE/MTB 1 : 1, R_f = 0.26) as a colourless oil. – ^{1}H NMR (200 MHz, $CDCl_3$): two diastereoisomers, ratio 1 : 1, partly doubled signal set; δ/ppm = 1.50 (d, *J* = 6.4 Hz, 3H), 1.51 (d, *J* = 6.8 Hz, 3H), 1.75–2.15 (m, 8H), 2.03 (s, 3H), 2.08 (s, 3H), 2.21–2.57 (m, 10H), 2.68 (ddd, *J* = 17.8 Hz, *J* = 9.6 Hz, *J* = 5.8 Hz, 2H), 5.86 (q, *J* = 6.6 Hz, 2H), 7.25–7.39 (m, 10H). – $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$): two diastereoisomers, partly doubled signal set; δ/ppm = 19.50 (CH_2), 21.98 (CH_3), 22.08 (CH_3), 26.85 (CH_2), 27.11 (CH_2), 29.81 (CH_3), 29.85 (CH_3), 34.28 (CH_2), 37.94 (CH_2), 38.37 (CH_2), 38.69 (CH_2), 58.91 (C), 58.99 (C), 73.44 (CH), 73.46 (CH), 125.80 (CH), 125.86 (CH), 127.95 (CH), 128.00 (CH), 128.50 (CH), 128.53 (CH), 141.04 (C), 141.10 (C), 170.47 (C), 170.56 (C), 207.66 (C), 207.73 (C), 214.39 (C), 214.65 (C). – MS (EI, 70 eV); *m/z* (%): 303 (23) [M + H^+], 199 (50) , 170 (20), 105 (100) [$PhCHMe^+$]. – IR (ATR): ν_{max}/cm^{-1} = 2977 (m), 1748 (s), 1717 (vs), 1452 (m), 1372 (m), 1258 (m), 1230 (m), 1208 (m), 1165 (s), 1116 (m), 1062 (s), 1029 (m), 700 (m). – Mol. mass calcd. 303.1596 ($C_{18}H_{23}O_4$), found 303.1591 (M + H^+, HRMS).

$C_{18}H_{22}O_4$	Calcd.: C 71.50	H 7.33
(302.37)	Found: C 71.19	H 7.40.

(1S,2R)-(–)-endo-Borneyl 2-oxo-1-(3-oxobutyl)cyclopentanecarboxylate (**3d**)

Following the general procedure (1*S*,2*R*)-(–)-*endo*-borneyl ester **1d** (300 mg, 1.13 mmol), MVK (116 mg, 1.65 mmol) and $FeCl_3 \cdot 6\ H_2O$ (15 mg, 0.055 mmol) in CH_2Cl_2 (1 ml) yielded the product **3d** (315 mg, 0.942 mmol, 83%) after chromatography (PE/MTB 1 : 1, R_f = 0.33) as a colourless oil. – $[\alpha]_D^{23}$ = –30 (c = 2.8 g/l, $CHCl_3$). – ^{1}H NMR (200 MHz, $CDCl_3$): two diastereoisomers, ratio 1 : 1, partly doubled signal set; δ/ppm = 0.80 (s, 3H), 0.81 (s, 3H), 0.85 (s, 6H), 0.88 (s, 6H), 1.12–1.36 (m, 5H), 1.59–2.18 (m, 17H), 2.12 (s, 6H), 2.24–2.54 (m, 10H), 2.64–2.84 (m, 2H), 4.80–4.96 (m, 2H). – $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$): two diastereoisomers, partly doubled signal set; δ/ppm = 13.39 (CH_3), 13.49 (CH_3), 18.75 (CH_3), 19.55 (CH_3), 19.56 (CH_2), 19.61 (CH_2), 26.97 (CH_2), 27.06 (CH_2), 27.09 (CH_2), 27.88 (CH_2), 27.99 (CH_2), 29.87 (CH_3), 34.37 (CH_2), 34.49 (CH_2), 36.64 (CH_2), 36.75 (CH_2), 37.96 (CH_2), 38.02 (CH_2), 38.84 (CH_2), 44.71 (CH), 44.74 (CH), 47.76 (C), 48.77 (C), 48.92 (C), 58.85 (C), 58.96 (C), 80.94 (CH), 81.14 (CH), 171.57 (C), 171.62 (C), 207.73 (C), 214.60 (C), 214.71 (C). – MS (EI, 70 eV); *m/z* (%): 334 (4) [M^+], 198 (10), 181 (8), 170 (13), 137 (100), 121 (10), 111 (11), 95 (22), 93 (14), 81 (30). – IR (ATR): ν_{max}/cm^{-1} = 2955 (s), 2882 (m), 1748 (s), 1718 (vs), 1454 (m), 1406 (m), 1367 (m), 1261 (m), 1232 (s), 1162 (s), 1115 (s), 1045 (m), 1022 (s), 994 (m), 980 (m). – Mol. mass calcd. 334.2144, found 334.2147 (HRMS).

$C_{20}H_{30}O_4$	Calcd.: C 71.82	H 9.04
(334.46)	Found: C 71.69	H 9.24.

(1R,3R,4S)-(–)-Menthyl 2-oxo-1-(3-oxobutyl)cyclopentanecarboxylate (**3e**)

Following the general procedure (1*R*,3*R*,4*S*)-(–)-menthyl ester **1e** (402 mg, 1.51 mmol), MVK (116 mg, 1.66 mmol) and $FeCl_3 \cdot 6\ H_2O$ (16 mg, 0.075 mmol) in CH_2Cl_2 (0.4 ml) yielded the product **3e** (496 mg, 1.47 mmol, 97%) after chromatography (PE/MTB 2 : 1, R_f = 0.23) as a colourless oil. – $[\alpha]_D^{23}$ = –40 (c = 4.0 g/l, $CHCl_3$). – ^{1}H NMR (200 MHz, $CDCl_3$): δ/ppm = 0.72 (d, *J* = 6.9 Hz, 3H), 0.81–1.06 (m, 3H), 0.87 (d, *J* = 6.9 Hz, 3H), 0.89 (d, *J* = 6.4 Hz, 3H), 1.29–1.51 (m, 2H), 1.61–1.71 (m, 2H), 1.73–2.18 (m, 7H), 2.12 (s, 3H), 2.26–2.52 (m, 4H), 2.61–2.80 (m, 1H), 4.67 (dt, *J* = 10.9 Hz, *J* = 4.4 Hz, 1H). – $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$): two diastereoisomers, partly doubled signal set; δ/ppm = 15.68 (CH_3), 15.70 (CH_3), 19.42 (CH_2), 19.46 (CH_2), 20.62 (CH_3), 20.69 (CH_3), 21.80 (CH_3), 22.81 (CH_2), 22.89 (CH_2), 25.78 (CH_3), 25.91 (CH_3), 26.78 (CH_2), 26.87 (CH_2), 29.73 (CH), 31.20 (CH), 33.97 (CH_2), 34.44 (CH_2), 37.69 (CH_2), 37.88 (CH_2), 38.69 (CH_2), 40.21 (CH_2), 40.43 (CH_2), 46.64 (CH), 46.72 (CH), 58.75 (C), 59.04 (C), 75.24 (CH), 75.29 (CH), 170.70 (C), 170.90 (C), 207.58 (C), 214.51 (C), 214.58 (C). – MS (EI, 70 eV); *m/z* (%): 336 (1) [M^+], 198 (24), 170 (100), 97 (16), 83 (38). – IR (ATR): ν_{max}/cm^{-1} = 2956 (vs), 2929 (vs), 2871 (s), 1748 (vs), 1717 (vs), 1454 (s), 1407 (m), 1387 (m), 1370 (s), 1317 (m), 1285 (m), 1258 (s), 1230 (vs), 1166 (vs), 1148 (vs), 1117 (s), 1097 (m), 1010 (m), 982 (m), 963 (m), 917 (m). – Mol. mass calcd. 336.2300, found 336.2297 (HRMS).

$C_{20}H_{32}O_4$	Calcd.: C 71.39	H 9.59
(336.47)	Found: C 71.22	H 9.51.

rac-1-Phenylethyl 2-acetyl-2-methyl-5-oxohexanoate (**3f**)

Following the general procedure keto ester **1f** (135 mg, 0.613 mmol), MVK (47 mg, 0.67 mmol) and $FeCl_3 \cdot 6\ H_2O$ (8.3 mg, 0.031 mmol) in CH_2Cl_2 (0.5 ml) were converted to yield the product **3f** after chromatography on SiO_2 (PE/MTB 1 : 1, R_f = 0.27) as a colourless oil (110 mg, 0.379 mmol, 62%). – ^{1}H NMR (400 MHz, $CDCl_3$): two diastereoisomers, ratio 45 : 55; δ/ppm = 1.28 (s, 3H), 1.29 (s, 3H), 1.51 (d, *J* = 6.6 Hz, 6H), 1.90–2.24 (m, 4H), 1.97 (s, 3H), 2.03 (s, 3H), 2.05 (s, 3H), 2.06 (s, 3H), 2.26 (ddd, *J* = 17.7 Hz, *J* = 10.1 Hz, *J* = 5.4 Hz, 2H), 2.38 (ddd, *J* = 17.5 Hz, *J* = 10.4 Hz, *J* = 5.4 Hz, 2H), 5.89 (q, *J* = 6.6 Hz, 1H), 5.90 (q, *J* = 6.6 Hz, 1H), 7.21–7.33 (m, 10H). – $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$): two diastereoisomers, partly doubled signal set; δ/ppm = 18.95 (CH_3), 19.07 (CH_3), 21.60 (CH_3), 21.75 (CH_3), 26.02 (CH_3), 26.06 (CH_3), 28.14 (CH_2), 28.18 (CH_2), 29.66 (CH_3), 29.76

(CH_3), 38.20 (CH_2), 38.35 (CH_2), 58.57 (C), 73.42 (CH), 125.97 (CH), 126.10 (CH), 128.05 (CH), 128.11 (CH), 128.45 (CH), 140.60 (C), 140.64 (C), 171.59 (C), 171.62 (C), 204.98 (C), 205.06 (C), 207.07 (C), 207.14 (C). – MS (EI, 70 eV); *m/z* (%): 290 (1) [M^+], 142 (78), 126 (91), 105 (100), 98 (96). – IR (ATR): ν_{max}/cm^{-1} = 2983 (m), 1710 (vs), 1454 (m), 1356 (s), 1287 (m), 1253 (s), 1228 (s), 1209 (s), 1176 (s), 1117 (m), 1103 (m), 1060 (s), 1029 (m), 1007 (m), 994 (m), 763 (m), 700 (s). – $C_{17}H_{22}O_4$ (290.36): Mol. mass calcd. 290.1518, found 290.1524 (HRMS).

Isobutyl 2-oxo-1-(3-oxobutyl)cyclohexanecarboxylate (**3g**)

Following the general procedure keto ester **1g** (140 mg, 0.706 mmol), MVK (99 mg, 1.4 mmol) and $FeCl_3 \cdot 6\ H_2O$ (9.5 mg, 0.035 mmol) in CH_2Cl_2 (0.2 ml) were converted to yield the product **3g** after chromatography on SiO_2 (PE/MTB 1 : 1, R_f = 0.4) as a colourless oil (151 mg, 0.563 mmol, 80%). – ^{1}H NMR (200 MHz, $CDCl_3$): δ/ppm = 0.86 (d, J = 6.7 Hz, 6H), 1.20–2.11 (m, 8H), 2.05 (s, 3H), 2.19–2.48 (m, 4H), 2.52 (ddd, J = 15.9 Hz, J = 10.3 Hz, J = 5.4 Hz, 1H), 3.83 (d, J = 6.5 Hz, 2H). – ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$): δ/ppm = 18.91 (CH_3), 22.41 (CH_2), 27.34 (CH_2), 27.50 (CH), 28.30 (CH_2), 29.74 (CH_3), 36.46 (CH_2), 38.68 (CH_2), 40.84 (CH_2), 59.91 (C), 71.31 (CH_2), 171.89 (C=O), 207.48 (C=O), 207.64 (C=O). – MS (EI, 70 eV); *m/z* (%): 268 (10) [M^+], 240 (14) [M^+ – CO], 198 (52) [M^+ – MeCOCH=CH_2], 151 (100) [M^+ – Me – CO_2*i*Bu – H]. – IR (ATR): ν_{max}/cm^{-1} = 2959 (m), 2942 (m), 2873 (m), 1711 (vs), 1369 (m), 1243 (m), 1213 (m), 1188 (s), 1168 (s), 1135 (m), 1079 (m), 995 (m). – Mol. mass calcd. 268.1675, found 268.1677 (HRMS).

$C_{15}H_{24}O_4$	Calcd.: C 67.14	H 9.01
(268.35)	Found: C 66.73	H 8.92.

Isobutyl 2-oxo-1-(3-oxobutyl)cycloheptanecarboxylate (**3h**)

Following the general procedure keto ester **1h** (102 mg, 0.480 mmol), MVK (50 mg, 0.71 mmol) and $FeCl_3 \cdot 6\ H_2O$ (6.5 mg, 0.024 mmol) in CH_2Cl_2 (0.2 ml) were converted to yield the product **3h** after chromatography on SiO_2 (PE/MTB 1 : 1, R_f = 0.40) as a colourless oil (122 mg, 0.432 mmol, 90%). – ^{1}H NMR (200 MHz, $CDCl_3$): δ/ppm = 0.87 (d, J = 6.8 Hz, 6H), 1.44–2.20 (m, 11H), 2.06 (s, 3H), 2.26–2.64 (m, 4H), 3.84 (d, J = 6.5 Hz, 2H). – ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$): δ/ppm= 18.96 (CH_3), 24.82 (CH_2), 25.46 (CH_2), 27.53 (CH), 29.22 (CH_2), 29.80 (CH_2), 29.81 (CH_3), 34.02 (CH_2), 39.08 (CH_2), 42.13 (CH_2), 61.72 (C), 71.21 (CH_2), 172.42 (C=O), 207.65 (C=O), 209.45 (C=O). – MS (EI, 70 eV); *m/z* (%): 282 (6) [M^+], 212 (26) [M^+ – MeCOCH=CH_2], 208 (27), 165 (57), 150 (73), 95 (65), 57 (100) [*i*Bu^+]. – IR (ATR): ν_{max}/cm^{-1} = 2958 (m), 2934 (s), 2874 (m), 1716 (vs), 1456 (m), 1369 (m), 1356 (m), 1226 (s), 1165 (s), 992 (m), 942 (m). – Mol. mass calcd. 282.1831, found 282.1837 (HRMS).

$C_{16}H_{26}O_4$	Calcd.: C 68.06	H 9.28
(282.38)	Found: C 67.71	H 9.15.

Diethyl 3,8-dioxo-2-(3-oxobutyl)-decandioate (**3i**)

Following the general procedure bis-donor **1i** (134 mg, 0.468 mmol), MVK (34 mg, 0.48 mmol) and $FeCl_3 \cdot 6\ H_2O$ (6.3 mg, 0.023 mmol) in CH_2Cl_2 (1 ml) were converted to yield the product **3i** after chromatography on SiO_2 (PE/MTB 1 : 1, R_f = 0.23) as a colourless oil (126 mg, 0.354 mmol, 76%). – ^{1}H NMR (400 MHz, $CDCl_3$): δ/ppm = 1.26 (t, J = 7.1 Hz, 3H), 1.27 (t, J = 7.1 Hz, 3H), 1.52–1.62 (m, 4H), 2.03–2.10 (m, 2H), 2.12 (s, 3H), 2.44–2.64 (m, 4H), 2.48 (t, J = 7.1 Hz, 2H), 3.42 (s, 2H), 3.50 (t, J = 7.1 Hz, 1H), 4.17 (q, J = 7.2 Hz, 2H), 4.19 (q, J = 7.2 Hz, 2H). – ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$): δ/ppm = 14.05 (CH_3), 21.68 (CH_2), 22.65 (CH_2), 29.89 (CH_3), 40.45 (CH_2), 41.63 (CH_2), 42.59 (CH_2), 49.24 (CH_2), 57.34 (CH), 61.34 (CH_2), 61.43 (CH_2), 167.13 (C=O), 169.44 (C=O), 202.35 (C=O), 204.61 (C=O), 207.52 (C=O). – MS (EI, 70 eV); *m/z* (%): 357 (2) [M + H^+], 311 (34), 293 (41), 265 (18), 247 (14), 223 (16), 199 (28), 153 (100), 125 (46), 111 (96). – IR (ATR): ν_{max}/cm^{-1} = 1739 (vs), 1712 (vs), 1410 (m), 1368 (s), 1314 (m), 1239 (s), 1159 (s), 1096 (m), 1025 (s). – Mol. mass calcd. 357.1913 ($C_{18}H_{29}O_7$), found 357.1918 (M + H^+, HRMS).

$C_{18}H_{28}O_7$	Calcd.: C 60.66	H 7.92
(356.42)	Found: C 59.87	H 7.95.

Diethyl 3,8-dioxo-2,9-bis-(3-oxobutyl)-decandioate (**3j**)

Following the general procedure bis-donor **1i** (110 mg, 0.384 mmol), MVK (102 mg, 1.50 mmol) and $FeCl_3 \cdot 6\ H_2O$ (5.2 mg, 0.019 mmol) in CH_2Cl_2 (1 ml) were converted to yield the product **3j** after chromatography on SiO_2 (MTB, R_f = 0.30) as a colourless oil (111 mg, 0.261 mmol, 68%). – ^{1}H NMR (400 MHz, $CDCl_3$): δ/ppm = 1.26 (t, J = 7.1 Hz, 6H), 1.52–1.58 (m, 4H), 2.04–2.10 (m, 4H), 2.13 (s, 6H), 2.45–2.64 (m, 4H), 2.48 (t, J = 7.0 Hz, 4H), 3.49 (t, J = 7.1 Hz, 2H), 4.18 (q, J = 7.2 Hz, 4H). – ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$): δ/ppm = 14.05 (CH_3), 21.68 (CH_2), 21.69 (CH_2), 29.89 (CH_3), 40.45 (CH_2), 41.66 (CH_2), 57.35 (CH), 61.42 (CH_2), 169.44 (C=O), 204.58 (C=O), 207.50 (C=O). – MS (EI, 70 eV); *m/z* (%): 427 (2) [M + H^+], 409 (13), 381 (24), 363 (50), 335 (20), 317 (16), 223 (100), 205 (24) 177 (64). – IR (ATR): ν_{max}/cm^{-1} = 1737 (s), 1709 (vs), 1444 (w), 1409 (m), 1367 (m), 1233 (m), 1201 (m), 1156 (s), 1096 (m), 1065 (m), 1022 (m). – Mol. mass calcd. 427.2332 ($C_{22}H_{35}O_8$), found 427.2332 (M + H^+, HRMS).

$C_{22}H_{34}O_8$	Calcd.: C 61.95	H 8.04
(426.51)	Found: C 61.51	H 8.05.

Diethyl 1-(3-oxobutyl)-2,5-cyclohexanedione 1,4-dicarboxylate (**3k**)

Following the general procedure diethyl 2,5-cyclohexanedione 1,4-dicarboxylate (**1k**) (150 mg, 0.585 mmol), MVK (162 mg, 2.31 mmol) and $FeCl_3 \cdot 6\ H_2O$ (7.9 mg, 0.029 mmol) in CH_2Cl_2 (5 ml) were converted to yield the product **3k** after chromatography on SiO_2 (PE/MTB 1 : 1, R_f = 0.31) as a colorless oil (82.0 mg, 0.251 mmol, 43%). – ^{1}H NMR (400 MHz, $CDCl_3$), the compound exists completely in the enol-form: δ/ppm = 1.24 (t, J = 7 Hz, 3H), 1.30 (t, J = 7 Hz, 3H), 1.98 (ddd, J = 5.7 Hz, J = 9.9 Hz, J = 15.4 Hz, 1H), 2.14 (s, 3H), 2.17 (ddd, J = 5.6 Hz, J = 9.9 Hz, J = 14.5 Hz, 1H), 2.44 (ddd, J = 5.5 Hz, J = 9.9 Hz, J = 15.4 Hz, 1H), 2.50 (d, J = 17.5 Hz, 1H), 2.59 (ddd, J = 5.5 Hz, J = 9.7 Hz, J = 15.3 Hz, 1H), 3.06 (dd, J = 0.7 Hz, J = 21.0 Hz, 1H), 3.11 (d, J = 17.4 Hz, 1H), 3.33 (dd, J = 0.8 Hz, J = 20.7 Hz, 1H), 4.20 (q, J = 7 Hz, 2H), 4.22 (q, J = 7 Hz, 2H), 12.18 (s, 1H). – ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$): δ/ppm = 13.91 (CH_3), 14.10 (CH_3), 26.44 (CH_2), 29.88 (CH_3), 35.98 (CH_2), 37.16 (CH_2), 38.46 (CH_2), 57.55 (C), 60.91 (CH_2), 61.96 (CH_2), 94.24 (C), 168.39 (C), 170.25 (C), 170.86 (C), 203.19 (C), 206.93 (C). – MS (EI,

70 eV); *m/z* (%): 326 (13) [M^+], 280 (12) [M^+ – EtOH], 256 (64), 210 (100), 182 (14). – IR (ATR): ν_{max}/cm^{-1} = 1719 (vs), 1663 (s), 1625 (m), 1417 (m), 1368 (m), 1319 (m), 1281 (s), 1232 (s), 1192 (s), 1168 (s), 1095 (m), 1080 (m). – $C_{16}H_{22}O_7$ (326.35): Mol. mass calcd. 326.1366, found 326.1361 (HRMS).

Diethyl 1,4-bis-(3-oxobutyl)-2,5-cyclohexanedione-1,4-dicarboxylate (**3l**)

Following the general procedure diethyl 2,5-cyclohexanedione 1,4-dicarboxylate (**1k**) (200 mg, 0.780 mmol), MVK (221 mg, 3.15 mmol) and $FeCl_3 \cdot 6\ H_2O$ (10.5 mg, 0.0388 mmol) in CH_2Cl_2 (1 ml) were converted for 2 d at 45 °C to yield the product **3l** after chromatography on SiO_2 (MTB, R_f = 0.20) as reddish crystals (221 mg, 0.558 mmol, 72%); *m.p.* 114–120 °C. – ^{1}H NMR (400 MHz, $CDCl_3$): δ/ppm = 1.26 (t, *J* = 7.0 Hz, 6H), 2.00–2.10 (m, 2H), 2.14 (s, 6H), 2.18–2.30 (m, 2H), 2.38–2.54 (m, 4H), 2.64 (d, *J* = 15.8 Hz, 2H), 3.21 (d, *J* = 15.8 Hz, 2H), 4.17 (q, *J* = 7.0 Hz, 4H). – ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$): δ/ppm = 13.74 (CH_3), 28.37 (CH_2), 29.76 (CH_3), 38.03 (CH_2), 44.86 (CH_2), 59.34 (C), 62.27 (CH_2), 169.33 (C=O), 201.26 (C=O), 206.56 (C=O). – MS (EI, 70 eV); *m/z* (%): 397 (86) [M + H^+], 379 (80), 361 (20), 350 (24), 333 (18), 322 (100), 309 (66), 276 (94), 233 (25). – IR (ATR): ν_{max}/cm^{-1} = 1749 (s), 1711 (vs), 1369 (m), 1297 (m), 1262 (m), 1208 (s), 1195 (s), 1167 (s), 1136 (m), 1100 (s), 1063 (m), 1026 (s). – Mol. mass calcd. 397.1862 ($C_{20}H_{29}O_8$), found 397.1865 (M + H^+, HRMS).

$C_{20}H_{28}O_8$	Calcd.: C 60.59	H 7.12
(396.44)	Found: C 60.19	H 7.03.

1,9-Bis(1-ethoxycarbonyl-2-oxocyclopentyl)-3,7-nonadione (**3m**)

Following the general procedure ethyl 2-oxocyclopentanecarboxylate (**1m**) (118 mg, 0.756 mmol), bis-acceptor **2b** (23.0 mg, 0.151 mmol) and $FeCl_3 \cdot 6\ H_2O$ (2 mg, 0.007 mmol) in CH_2Cl_2 (1 ml) were converted to yield the product **3m** after chromatography on SiO_2 (PE/MTB 1 : 1, R_f = 0.05) as a colourless oil (47.0 mg, 0.101 mmol, 67%). – ^{1}H NMR (400 MHz, $CDCl_3$): δ/ppm= 1.24 (t, *J* = 7.1 Hz, 6H), 1.80 (p, *J* = 6.9 Hz, 2H), 1.91 (ddd, *J* = 5.5 Hz, *J* = 9.8 Hz, *J* = 14.8 Hz, 2H), 1.95–2.05 (m, 4H), 2.10 (ddd, *J* = 5.9 Hz, *J* = 9.6 Hz, *J* = 14.4 Hz, 2H), 2.24–2.48 (m, 10H), 2.41 (t, *J* = 7.1 Hz, 4H), 2.64 (ddd, *J* = 5.8 Hz, *J* = 9.5 Hz, *J* = 15.4 Hz, 2H), 4.16 (q, *J* = 7.2 Hz, 4H). – ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$): δ/ppm = 14.08 (CH_3), 17.59 (CH_2), 19.57 (CH_2), 26.95 (CH_2), 34.32 (CH_2), 37.93 (CH_2), 37.98 (CH_2), 41.53 (CH_2), 59.02 (C), 61.43 (CH_2), 171.39 (C=O), 209.37 (C=O), 214.89 (C=O). – MS (EI, 70 eV); *m/z* (%): 464 (2) [M^+], 447 (24), 402 (20), 263 (98), 245 (62), 211 (42), 165 (56), 156 (40), 137 (98), 125 (66), 111 (53), 97 (64), 55 (100). – IR (ATR): ν_{max}/cm^{-1} = 2967 (m), 2940 (m), 2904 (m), 1747 (vs), 1715 (vs), 1448 (m), 1406 (m), 1367 (m), 1318 (m), 1259 (s), 1231 (s), 1161 (s), 1115 (m), 1096 (m), 1030 (m). – $C_{25}H_{36}O_8$ (464.56): Mol. mass calcd. 464.2410, found 464.2410 (HRMS).

Ethyl 1-(ethoxycarbonylmethyl)-1-cyclohexene-3-one-2-carboxylate (**5**)

Freshly distilled dialdehyde **4** (317 mg, 3.15 mmol) was added at 0 °C to a solution of anhydrous $SnCl_2$ (119 mg, 0.628 mmol) and ethyl diazoacetate (2.17 g, 19.0 mmol) in abs. CH_2Cl_2 (5 ml). After stirring for 3 h at ambient temperature the mixture was filtered through SiO_2 (MTB), the solvent was evaporated and the residue chromatographed on SiO_2 (PE/MTB 1 : 1, R_f = 0.22) to yield the condensation product **5** (752 mg, 2.96 mmol, 53%) as a colourless oil. – ^{1}H NMR (400 MHz, $CDCl_3$): δ/ppm = 1.26 (t, *J* = 7.0 Hz, 3H), 1.31 (t, *J* = 7.0 Hz, 3H), 2.04 (pentet, *J* = 6.8 Hz, 2H), 2.46 (t, *J* = 6.8 Hz, 2H), 2.52 (t, *J* = 7.0 Hz, 2H), 3.30 (s, 2H;), 4.16 (q, *J* = 7.0 Hz, 2H), 4.28 (q, *J* = 7.0 Hz, 2H). – ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$): δ/ppm = 14.06 (2 CH_3), 21.66 (CH_2), 30.55 (CH_2), 37.05 (CH_2), 40.84 (CH_2), 61.37 (2 CH_2), 134.67 (C), 155.02 (C), 165.87 (C=O), 168.53 (C=O), 194.88 (C=O). – MS (EI, 70 eV); *m/z* (%): 254 (12) [M^+], 208 (84) [M^+ – EtOH], 180 (51) [M^+ – EtOH – CO], 162 (100) [M^+ – 2 EtOH], 152 (33). – IR (ATR): ν_{max}/cm^{-1} = 2983 (m), 1732 (vs), 1675 (vs), 1633 (m), 1425 (m), 1390 (m), 1371 (s), 1350 (m), 1327 (s), 1304 (s), 1255 (vs), 1183 (vs), 1130 (s), 1096 (m), 1063 (s), 1044 (vs), 1028 (s). – $C_{13}H_{18}O_5$ (254.28): Mol. mass calcd. 254.1154, found 254.1155 (HRMS).

3,7-Dihydroxy-1,8-nonadiene (**7**)

A solution of freshly distilled dialdehyde **4** (3.60 g, 36.7 mmol) in abs. THF (20 ml) was dropwise added to vinylmagnesium bromide (108 mmol, 108 ml of a 1 mol/l solution in THF) at 0 °C. After stirring the reaction mixture for 1 h at ambient temperature, it was poured into 200 ml of a saturated aqueous NH_4Cl solution. The aqueous layer was extracted three times with MTB, the combined organic layers were dried ($MgSO_4$) and after filtration the solvent was evaporated. Kugelrohr distillation of the residue at 150 °C (oven temp.) in high vacuum yielded the dialcohol **7** (4.80 g, 30.7 mmol, 86%) as a colourless oil. – ^{1}H NMR (400 MHz, $CDCl_3$): δ/ppm = 1.40–1.62 (m, 8H), 4.12 (q, *J* = 5.1 Hz, 2H), 5.11 (dd, *J* = 1.2 Hz, *J* = 10.2 Hz, 2H), 5.23 (dt, *J* = 1.4 Hz, *J* = 17.3 Hz, 2H), 5.87 (ddd, *J* = 6.3 Hz, *J* = 10.5 Hz, *J* = 17.1 Hz, 2H). – ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$), mixture of two diastereoisomers: δ/ppm = 20.94 (CH_2), 21.01 (CH_2), 36.48 (CH_2), 36.58 (CH_2), 72.56 (CH), 72.70 (CH), 114.33 (CH_2), 114.38 (CH_2), 141.04 (CH), 141.08 (CH). – MS (EI, 70 eV); *m/z* (%): 156 (1) [M^+], 123 (9), 81 (15), 67 (30), 57 (82), 54 (100). – IR (ATR): ν_{max}/cm^{-1} = 3343 (br., s), 2938 (m), 2863 (m), 1644 (m), 1424 (s), 1320 (s), 1279 (m), 1123 (m), 1070 (s), 990 (vs), 920 (vs), 675 (s). – Mol. mass calcd. 156.1150, found 156.1159 (HRMS).

$C_9H_{16}O_2$	Calcd.: C 69.19	H 10.32
(156.23)	Found: C 68.76	H 10.58.

7-Hydroxy-3-oxo-1,8-nonadiene (**8**)

A solution of the dialcohol **7** (400 mg, 2.56 mmol) in abs. CH_2Cl_2 (5 ml) was added dropwise at 0 °C to a suspension of NMO (690 mg, 5.89 mmol), ground molecular sieves (1.28 g, 4 Å) and TPAP (45.0 mg, 1.28 mmol) in abs. CH_2Cl_2 (8 ml) and abs. MeCN (1 ml). After stirring 1 h at ambient temperature the mixture was filtered through SiO_2 (MTB), the solvent was evaporated and the product chromatographed on SiO_2 (PE/MTB 1 : 1, R_f = 0.16) to give the keto alcohol **8** (257 mg, 1.67 mmol, 65%) as a colourless oil. – ^{1}H NMR (400 MHz, $CDCl_3$): δ/ppm = 1.51–1.62 (m, 2H), 1.60 (s, br., 1H), 1.63–1.82 (m, 2H), 2.64 (t, *J* = 7.2 Hz, 2H), 4.11 (q, *J* =

6.1 Hz, 1H), 5.11 (td, J = 1.2 Hz, J = 10.5 Hz, 1H), 5.24 (td, J = 1.4 Hz, J = 17.3 Hz, 1H), 5.83 (dd, J = 1.2 Hz, J = 10.3 Hz, 1H), 5.87 (ddd, J = 6.1 Hz, J = 10.4 Hz, J = 16.9 Hz, 1H), 6.22 (dd, J = 1.2 Hz, J = 17.8 Hz, 1H), 6.36 (dd, J = 10.5 Hz, J = 17.7 Hz, 1H). – $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$): δ/ppm = 19.54 (CH_2), 36.27 (CH_2), 39.22 (CH_2), 72.67 (CH), 114.72 (CH_2), 128.11 (CH_2), 136.42 (CH), 140.86 (CH), 200.75 (C=O). – MS (EI, 70 eV); m/z (%): 136 (2) [M^+ – H_2O], 98 (20), 97 (32), 84 (17), 83 (32), 70 (83), 57 (38), 55 (100). – IR (ATR): ν_{max}/cm^{-1} = 3425 (br., s), 2980 (m), 2936 (s), 2871 (m), 1677 (vs), 1615 (s), 1403 (vs), 1372 (s), 1278 (s), 1242 (s), 1214 (s), 1188 (s), 1101 (s), 1067 (s), 1041 (s), 990 (vs), 966 (vs), 923 (vs), 845 (m), 751 (m). – $C_9H_{14}O_2$ (154.21).

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